

AUDELS ELECTRIC MOTOR GUIDE

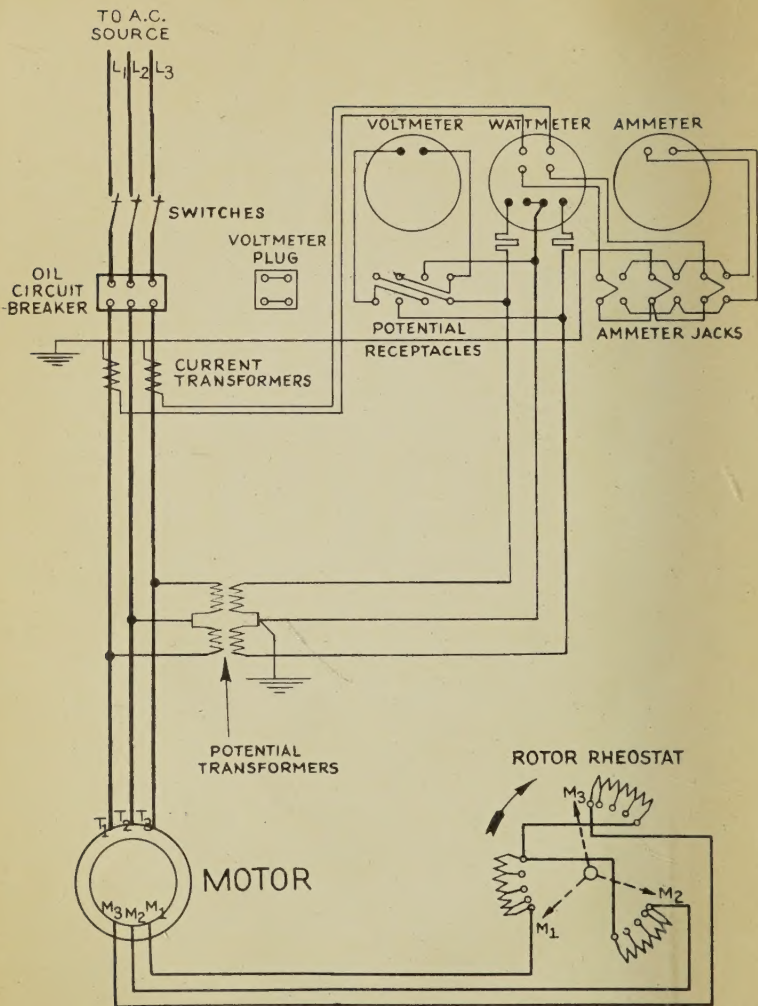
COVERING
CONSTRUCTION
CONTROL
AND
MAINTENANCE
INCLUDING
ARMATURE
WINDING

— *by* —

EDWIN P. ANDERSON



THEO. AUDEL & CO., PUBLISHERS
49 WEST 23RD STREET., NEW YORK 10, N.Y.



FRONTISPIECE.—Typical wiring diagram of large manually operated wound rotor induction motor and associated meters. For further details see Chapter 10.

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NEW YORK

Reprinted, 1951

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FOREWORD

The purpose of this book is to give practical information on the selection, installation, operation, maintenance, control and winding of electric motors.

The importance of a fundamental understanding of electric motors will be fully realized, if it be considered that electric motors are the means of utilizing power, in over ninety per cent of industrial applications.

The growth of the utilization of electric motors in industry and homes, however, cannot be measured by any set of figures, because of their constantly increasing use.

Each of the thousands of motors installed requires various methods of control, depending upon the particular application and may vary from a simple face plate starter, to a large and complicated automatic control, with several remote control push button stations. It is to supply the need for practical information on all phases of motor control and associated maintenance, that this book has been written.

The *first part* of this book deals with the fundamental characteristics and control methods of the various types of motors together with methods of installation and maintenance.

The *second part* is devoted to WINDING methods and REWINDING of motors, since a thorough knowledge of winding is of the utmost importance in both the motor repair shop and manufacturing plant.

In conclusion, the author takes this opportunity to thank the various persons and manufacturers for motor data and illustrative material, in particular to S. G. Norlander, professional electrical engineer, for reading of manuscript and valuable suggestions in regards to text matter arrangements.

To E. W. Lawson, for particularly efficient secretarial work.

To the Publishers, for valuable aid in preparation of this book.

EDWIN P. ANDERSON.

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Learn to use the index; all subjects covered are listed under their proper headings; it is also suggested to look up closely allied subjects for side lights on your problems.

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CHAPTER 1**Motor Working Principles**

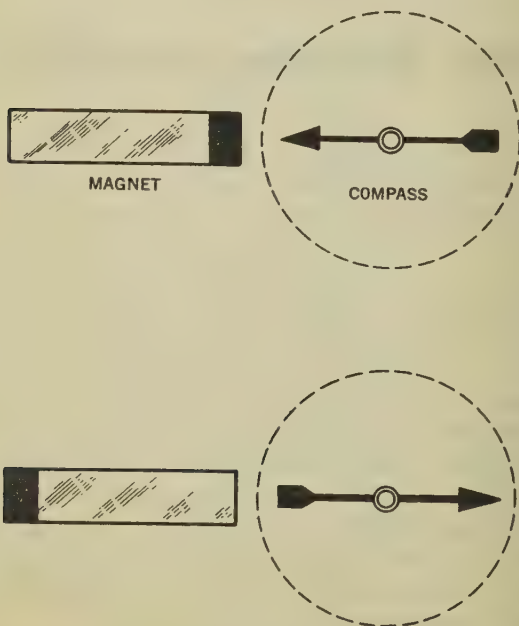
In order to obtain a clear conception of the principles upon which the electric motor operates, it is necessary first to understand the fundamental laws of *magnetism* and *magnetic induction*.

It will not be necessary to have a great multiplicity of expensive laboratory instruments at our disposal to obtain this knowledge—instead, children's toy magnets, automobile accessories, etc., will suffice. It is from these simple things that the necessary knowledge about the behavior of permanent magnets and the magnetic needle will be obtained.

In our early school days, we learned that the earth is a huge permanent magnet with its North magnetic pole somewhere in Hudson's Bay region and that the compass-needle points toward the magnetic pole; that is, the point of the compass needle is a South Pole, magnetically speaking. The compass is thus an indication of magnetism.

The two spots on the magnet which point, one to the North and the other to the South are called the *poles*—one is called the *North-seeking pole (N)* and the other the *South-seeking pole (S)*.

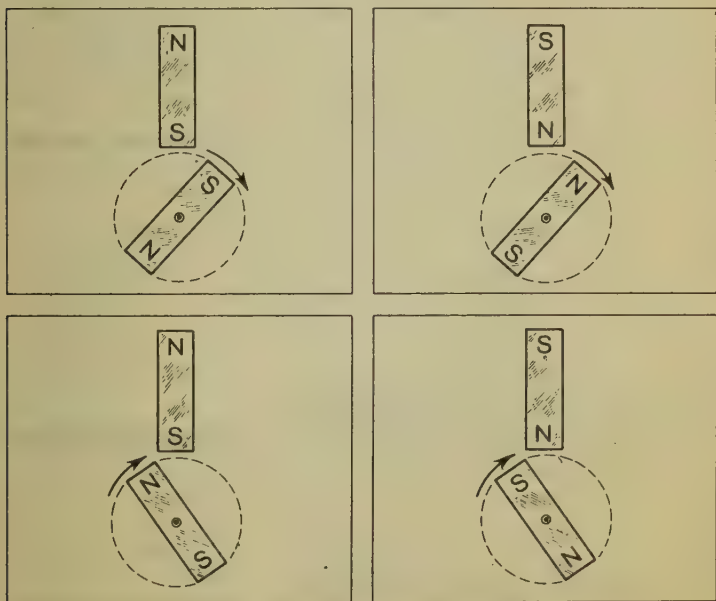
Magnetic Attraction and Repulsion.—If we bring the South-seeking or S pole of a magnet near the S pole of a suspended magnet, as in figs. 3 to 6, we find that the poles repel each other. If we bring the two N poles together, they also repel each other, but if we bring an N pole toward the S pole of the moving magnet, or a S pole toward the N pole, they attract each other. That is, *like poles repel each other, and unlike poles attract each other.*



FIGS. 1 and 2.—Illustrating the effect on the magnetic needle when moved towards a permanent magnet. If several permanent magnets be available, it is possible to determine the polarity of each and mark it as indicated. The only fact that should be remembered is that the compass needle is *attracted* by the *North Pole* of a permanent magnet and *repelled* by the *South Pole*.

It can also be shown by experiments, that these attractive or repulsive forces between magnetic poles vary inversely as the square of the distance between the poles.

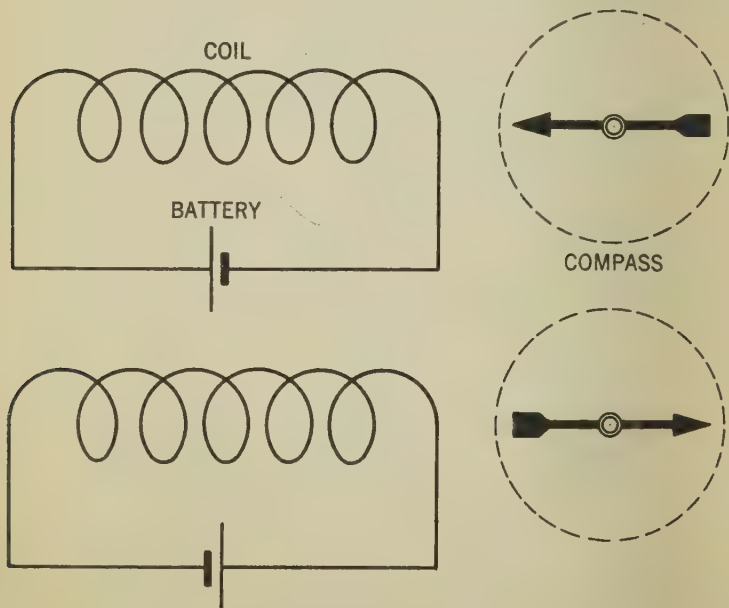
Effects of an Electric Current.—As a further experiment, connect a coil to a battery as shown in figs. 7 and 8. Here we find that the compass points at one end of the coil, but that if the battery connections be reversed, the compass points away from that end. Thus, it is found that the direction of the current through the coil affects the compass in a manner similar to the permanent magnet in the previous experiment.



FIGS. 3 to 6.—Illustration showing how like poles of permanent magnets repel one another while unlike poles attract one another.

In the beginning of the Eighteenth Century, Oersted made the discovery showing the connection between magnetism and electricity. He observed that if a wire connecting the poles of a battery was held over a compass needle, the *north pole* of the needle was deflected toward the *west* when the current flowed from *south to north*, as shown in fig. 9, while a wire placed under the compass needle caused the *north* of the needle to be deflected toward the *east*.

The Magnetic Field of an Electric Current.—Inasmuch as the compass needle indicates the direction of magnetic lines of force, it is evident from Oersted's experiment that an electric



FIGS. 7 and 8.—Showing the effect of the direction of current upon the compass needle.

current must set up a magnetic field at right angles to the conductor. This can be shown by an experiment illustrated in fig. 10. If a strong current be sent through a vertical wire which passes through a horizontal piece of cardboard filled with iron filings, a gentle tap of the board causes the iron filings to arrange themselves in concentric rings about the wire. By placing a compass at various positions on the board, we observe that the direction of these lines of force is as given in fig. 10.

A convenient rule for remembering the direction of the magnetic flux around a straight wire carrying current, is the so-called thumb rule. With reference to fig. 11, it will be observed that if the *wire be held with the right hand, and with the thumb in the direction of the current, the fingers will point in the direction of the magnetic field.*

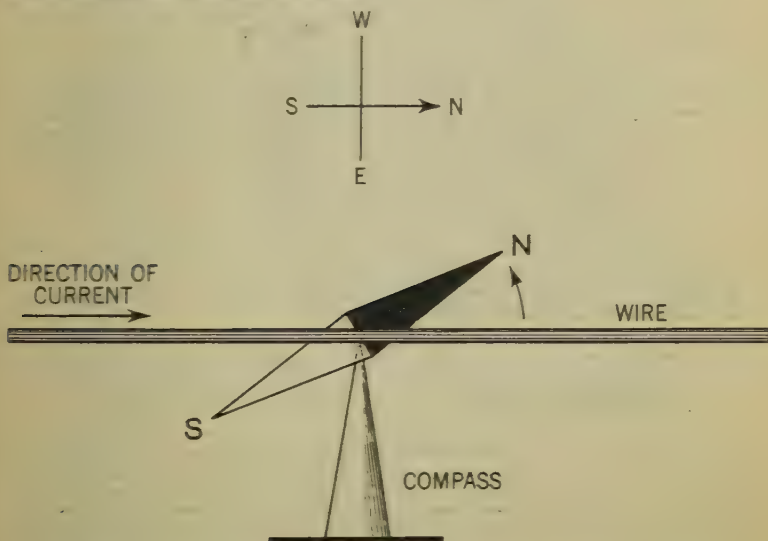


FIG. 9.—Illustrating how current in a wire causes a deflection of the compass needle.

Conversely, if the direction of the magnetic field around a conductor be known the direction of the current in the same conductor can be found by applying this rule.

The Electromagnet.—A soft iron core surrounded by a coil of wire is called an *electromagnet*. The electromagnet owes its great utility not so much to its great strength as to its ability to change its magnetic strength with the strength of the applied

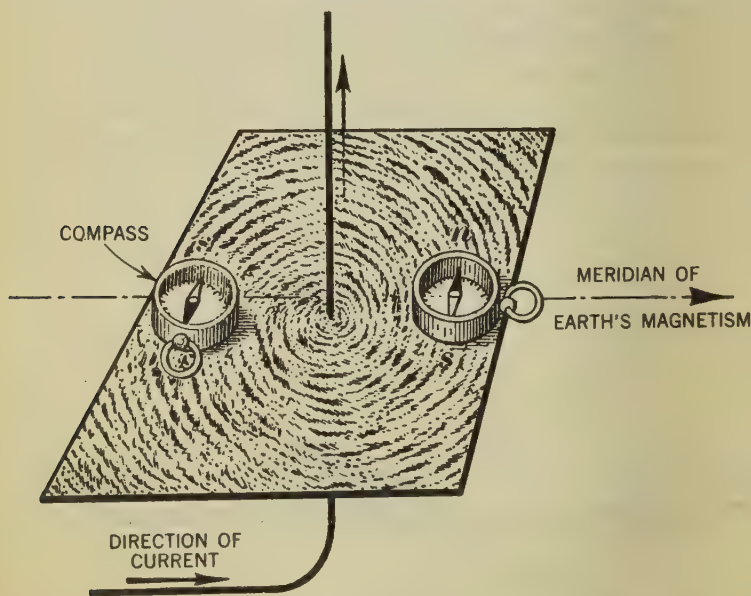


FIG. 10.—Experiment showing direction of lines of force in the magnetic field surrounding conductor carrying an electric current. If a piece of wire is pierced through the center of a sheet of cardboard, and carried vertically for a short distance, it will be observed that at a light tapping of the board iron filings will arrange themselves in circular paths around the wire. This indicates the contours or forms of the magnetic field surrounding the conductor. If the direction of the current through the conductor be as shown, the compass needles will take the position as indicated. Thus compass needles may also be used to indicate direction of currents.

current. Such an electromagnet is a magnet only when current flows through its coil. When the current is interrupted, the iron core returns almost to its natural state. This loss of magnetism is, however, not absolutely complete since a very small amount called *residual magnetism* remains for a longer or shorter period of time.

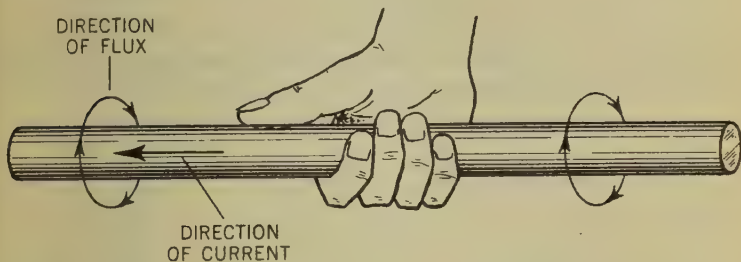


FIG. 11.—Illustrating *right hand rule* to determine the direction of magnetic flux around a current carrying conductor.

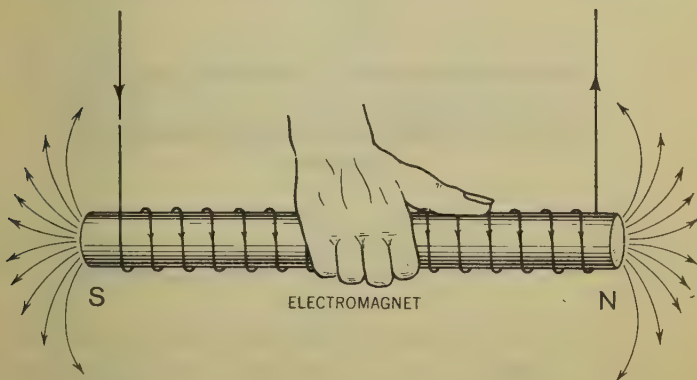


FIG. 12.—Illustrating the *thumb rule* to determine the direction of the *North Pole* in an electromagnet.

An *electromagnet* is a part of nearly all *electrical devices*, including electric bells, telephones, motors and generators.

The polarity of an electromagnet may be determined with assistance of the previously given thumb rule as used for a straight wire as follows: *Grasp the coil with the right hand so that the fingers point in the direction of the current in the coil, and the thumb will point to the north pole of the coil.*

The strength of an electromagnet depends on the product of the strength of the current (in amperes) by the number of loops of wire (turns), that is, the *ampere turns* of the coil.

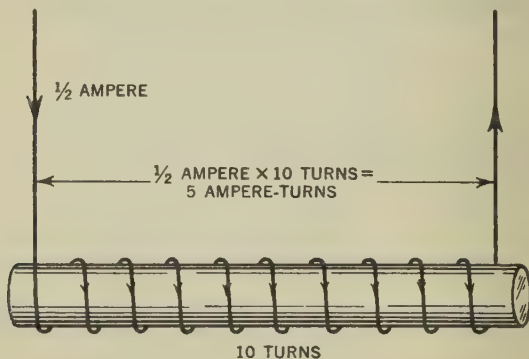


FIG. 13.—Illustrating the meaning of *Ampere-turns*. By definition, the ampere-turns are equal to the product of the current passing through a coil multiplied by the number of turns in the coil. Thus, for example, $\frac{1}{2}$ ampere $\times$ 10 turns = 5 ampere-turns.

In practical electromagnets, it is customary to make use of both poles by bending the iron core and the coil in form of a horseshoe. It is from this form, the name *horseshoe-magnet* has been derived.

Currents Induced by Magnets.—If the ends of a fine coil of wire having many turns be connected to a sensitive galvanometer, as shown in fig. 14, and the coil be moved up and down over one pole of a horseshoe magnet, a deflection of the galvanometer pointer will be observed.

It will also be noted that in lowering the coil the deflection of the galvanometer pointer will be in opposite direction from that of the needle when the coil was raised.

When the coil is lowered and held down, the galvanometer pointer comes back to zero. Also, as the coil is moved up and down slowly several times, the deflection of the galvanometer

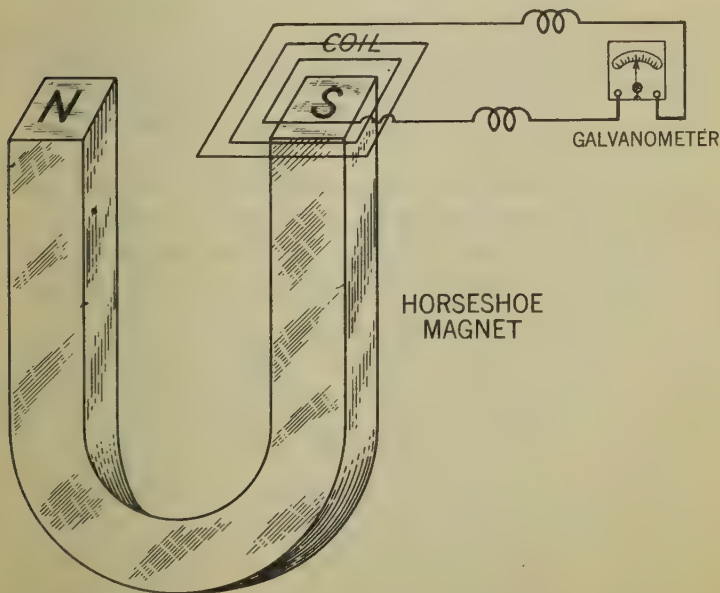


FIG. 14.—Illustrating how the movement of a coil in a magnetic field generates an electric current.

pointer becomes less each time. This experiment shows that it is possible to produce a momentary electric current without apparent electrical source.

The electric current produced by moving the coil in a magnetic field is called an *induced current*. It is evident from the experiment that the current is induced only when the wire is *moving* and the direction of the current is reversed when the motion changes direction. Since an electric current is always made to flow by an electromotive force (*e.m.f.*), the motion of a coil in the magnetic field must generate and produce an *induced electromotive force*.

Direction of Induced Current.—The direction of induced currents may be stated as follows: *An induced current has such a direction that its magnetic action tends to resist the motion by which it is produced. This is known as Lenz's Law.*

Wire Cutting Lines of Magnetic Force.—The most useful application of induced currents is obviously the fact that it made possible the construction of electrical machinery of all sorts, the most well known of which is the *generator* and *motor*.

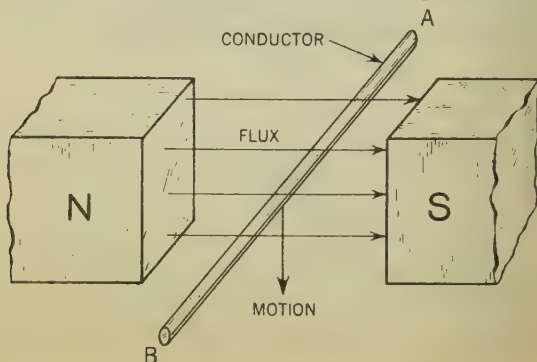


FIG. 15.—A voltage in a wire is induced by cutting the flux.

A simple way to obtain the fundamental understanding of the generator is to think of the induced electromotive force (*e.m.f.*) produced in a single wire when it is moved across a magnetic field. Suppose the wire *AB* is pushed down the magnetic field shown in fig. 15. An induced *e.m.f.* is set up in *AB*, which makes *B* at higher potential than *A* and can be shown by connecting *A* and *B* with a voltmeter.

As long as the wire remains stationary no current flows. Even if the wire does move, if it be in a direction parallel to the lines of force, no current flows. Briefly, a wire must move so as to cut lines of magnetic force, in order to have an *e.m.f.* induced in it.

The Direct Current Generator.—A machine converting mechanical energy into electrical energy is called a **generator**. Its essential parts are:

1. The *magnetic field*, usually produced by permanent magnets, and
2. A *moving coil* or coils of copper wire, which is called the *armature*.

In a direct current machine, fig. 16, a mechanical device called a *commutator* is used to reverse the connections to the revolving conductors in the generator at the instant the current in them is reversing. Each end of the loop of wire is connected to one segment of the commutator, each segment being insulated from the others.

The sliding contacts, or brushes, are so placed that the current always flows from the loop into one brush and from the other into the loop regardless of which relative direction the current in the loop itself flows. In this way the brushes carry current flowing in one direction only. The brushes or terminals are

designated by the terms “*positive*” and “*negative*” or “*plus*” and “*minus*,” simply to distinguish the direction in which the current is assumed to flow.

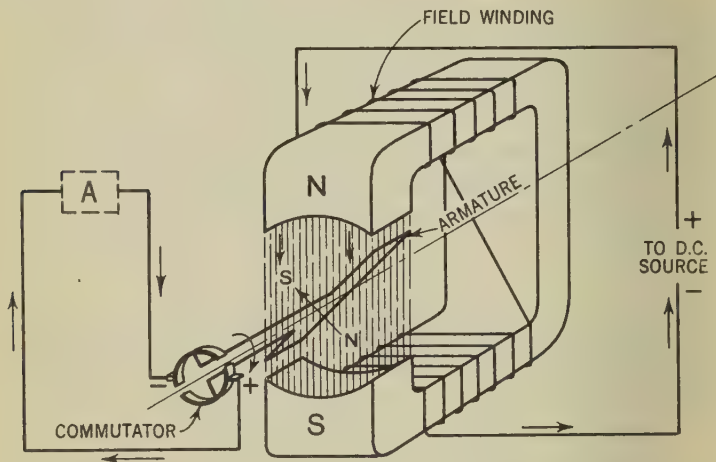


FIG. 16.—Illustrating an elementary *direct current* generator. A commutator is employed to keep the current in the load circuit flowing continually in the same direction.

The Direct Current Motor.*—A machine converting electrical energy into mechanical energy is called a **motor**. The functions of a generator and motor are interchangeable, in that a *generator* may be operated as a *motor* and vice versa.

Structurally the two machines are identical. The motor, like the generator, consists of an electromagnet, an armature and a commutator with its brushes.

*NOTE.—Since all the motors discussed here are more fully covered in subsequent chapters, the present treatment serves only the purpose of giving the simple fundamentals upon which motors operate.

Fig. 16 will serve to illustrate the operation of a direct current motor as well as a generator. The magnetic field will be the same for the motor as indicated, because of current flowing in the field windings. Now let the outside circuit at *A* have a voltage which causes a current to flow in the armature loop as indicated by the arrows.

It will be remembered from the foregoing that any current flowing in a loop or coil of wire produces a magnetic field. This is exactly what happens in the armature of this motor, and we have thus produced a second magnetic field with poles *N* and *S* perpendicular to the armature loop, but the *north pole* of main magnetic field attracts the *south pole* of the armature, and since the loop is free, it will revolve.

At the instant that the *north* and *south* poles become exactly opposite, however, the commutator reverses the current in the armature, making like poles opposite and the loop is then repelled and forced to revolve further.

Again the armature current is reversed when unlike poles approach and the armature is free to revolve. This continues as long as there is current in the armature and field windings.

It should be observed that in an actual motor there are many loops called armature coils, each with its terminals connected to adjacent commutator segments. Hence the attracting and repelling action is correspondingly more powerful and also more uniform than that of the weak and unstable action obtained with the single loop armature here described.

The various types of direct current motors as well as their operating characteristics and control methods are fully treated in a later chapter.

The Single-Phase Alternating Current Generator.—When a coil of wire is rotated in a magnetic field, the current changes its direction every half turn. Thus there are two alternations of the current for each revolution of a bipolar machine. As previously noted, this alternating current is rectified by the use of a commutator in a direct current generator. In an alternating current generator, also termed *alternator*, the current induced in the armature is led out through slip rings or collector rings as shown in fig. 17.

A magnetic field is established between the *north pole* and the *south pole* by means of an exciting current flowing in the winding *W*. A loop of wire *L* in this field is arranged so that it can be rotated on the axis *X* and the ends of this loop are brought out to slip rings *SS*, on which brushes *BB* can slide.

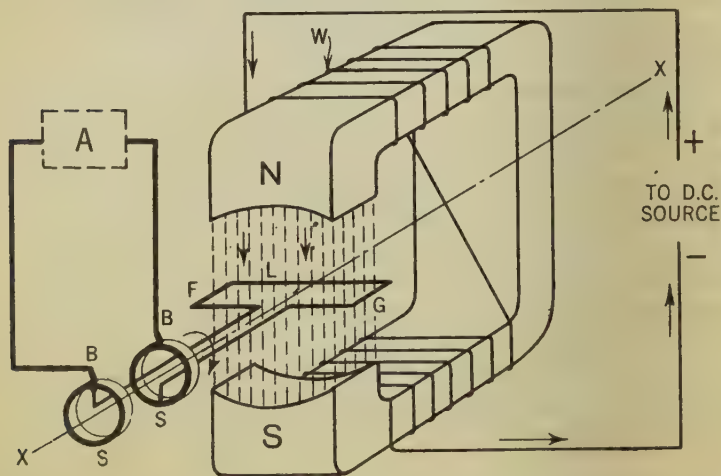


FIG. 17.—An elementary alternating current generator (alternator) of the revolving armature type. The slip rings and brushes are employed as a convenient means of collecting the current from the armature.

The circuit of which this rotating loop is a part is completed through the slip rings at *A*. When the loop is rotating, the conductors *F* and *G* have a voltage produced in them which will cause a current to flow out to *A* where the circuit is completed.

The simplified machine represented in fig. 17 is a two-pole single-phase revolving armature alternating current generator. The magnetic field, that is, the coils of wire and the iron core, are called simply the *field* of the generator. The rotating loop in which the voltage is induced is called the *armature*.

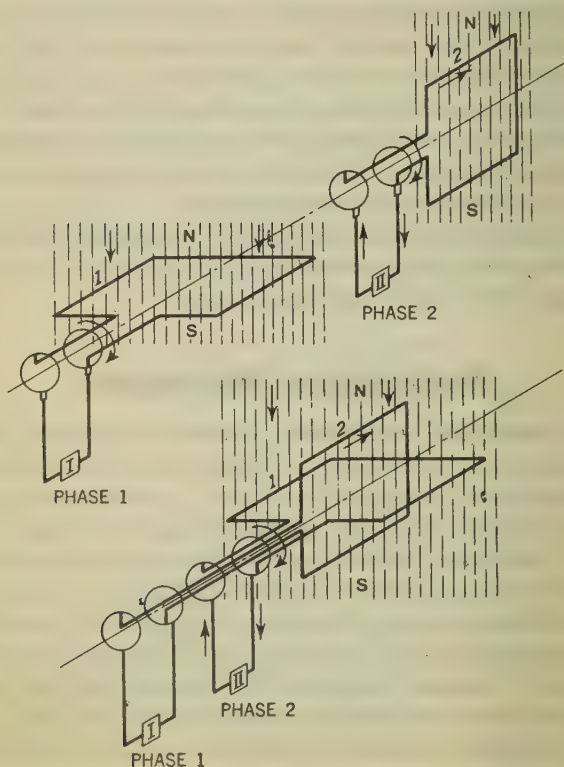
The revolving armature type of generator is generally used only on small machines, whereas large machines almost without exception are built with revolving fields.

If the voltage completes 60 cycles in one second, the generator is termed a *60-cycle machine*. The current that this voltage will cause to flow, will be a 60 cycle current.

Polyphase Machines

The Two-Phase Alternating Current Generator.—A two-phase generator is actually a combination of two single-phase generators shown in figs. 18 and 19. The armatures of these machines are mounted on one long shaft and must revolve together, always at right angles to each other, as shown in fig. 20. If the voltage waves or curves be plotted, as in fig. 21, we find that when phase 1 is in such a position that the voltage in it is a maximum, phase 2 is in such a position that the voltage in it is zero. A quarter of a cycle later phase 1 will be zero and phase 2 will have advanced to a position previously occupied by 1, and its voltage will be at a maximum. Thus phase 2 follows phase 1 and the voltage is always exactly a quarter of a cycle behind, due to the relative mechanical positions of the armatures.

The Three-Phase Alternating Current Generator.—It has been found economical to have more than one coil for each pole of the field. It is because of this that present day alternating current generators are built *three-phase*, in which there are three sets of coils on the armature. Here three sets of armature coils



FIGS. 18 to 20.—Illustrating the fundamental construction of a two-phase alternating current machine. When the two single machines shown in figs. 18 and 19 are combined in one magnetic field as shown in fig. 20, the result is a two-phase alternating current machine.

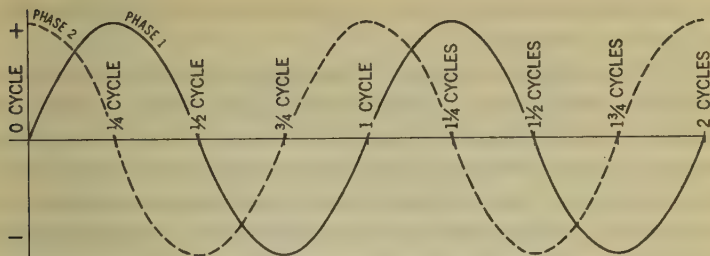


FIG. 21.—Sinusoidal curves representing voltages in two separate loops of wire rotating together always at right angle to one another. Voltage curves shown are generated by two-phase machines such as that shown in fig. 20.

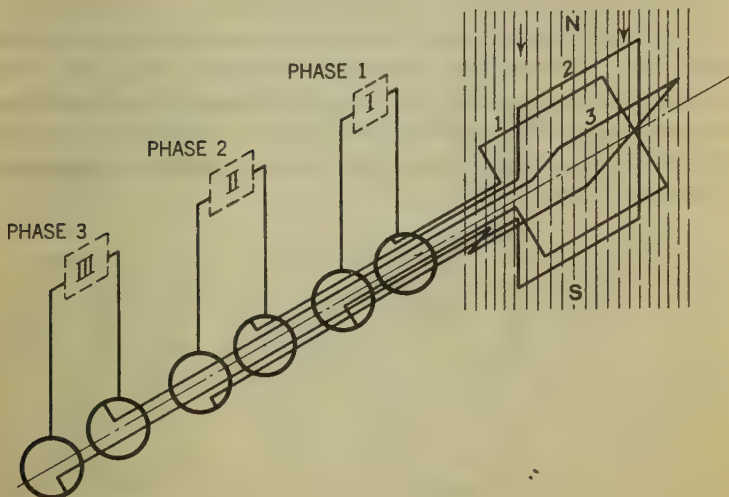


FIG. 22.—If three separate loops of wire, each loop displaced from one another at an equal angle, be made to rotate in the same magnetic field, and each loop brought out to a separate pair of slip rings, the result is a three-phase alternating current machine.

may each be used separately to supply electricity to three separate lighting circuits.

In a three-phase generator, three single-phase coils (or windings) are combined on a single shaft and rotate in the same magnetic field as shown in fig. 22. Each end of each coil is brought out to a slip ring and an external circuit. In a three-phase generator, the voltage in each phase alternates exactly a third of a cycle after the one ahead of it, due to the mechanical arrangement of the windings in the machine. Thus, when the voltage in phase 1 is approaching a positive maximum, as shown in fig. 23, that in phase 2 is at a negative maximum and the voltage in phase 3 is declining. A succeeding variation of these voltages are as indicated.

In practice, each end of each phase winding is not brought out to a separate slip ring in a three-phase machine, but the three phases are all connected together as shown in fig. 24. This arrangement makes only three leads necessary for a three-phase winding, each lead serving two phases. Then each pair of wires acts like a single-phase circuit, substantially independent of the other phases.

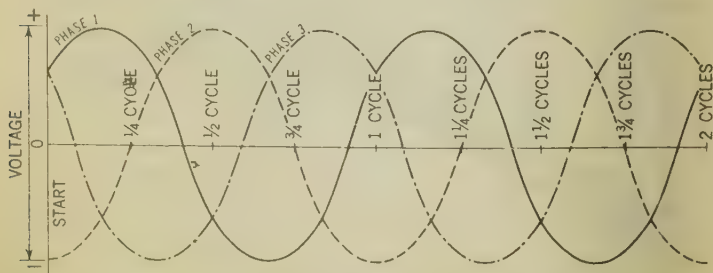


FIG. 23. —Sinusoidal curves illustrating the voltage variations in a three-phase machine. It should be observed that at every point the instantaneous value of one voltage is equal and opposite to the other two. The voltage values above the zero line is always positive and that under the zero line is negative.

The Synchronous Motor.—Any A.C. generator can be employed as a motor, provided it is first brought up to the exact speed of a similar generator supplying the current to it and put in step with the alternations of the supplied current. Such a machine is called a *synchronous motor*. Due, however, to complications in starting, most synchronous motors of late construction are equipped with a damper or amortisseur winding which produces a starting torque, permitting them to be started as induction motors.

Speed of Synchronous Motors.—The speed of a synchronous motor depends upon the frequency of the current supplied to it

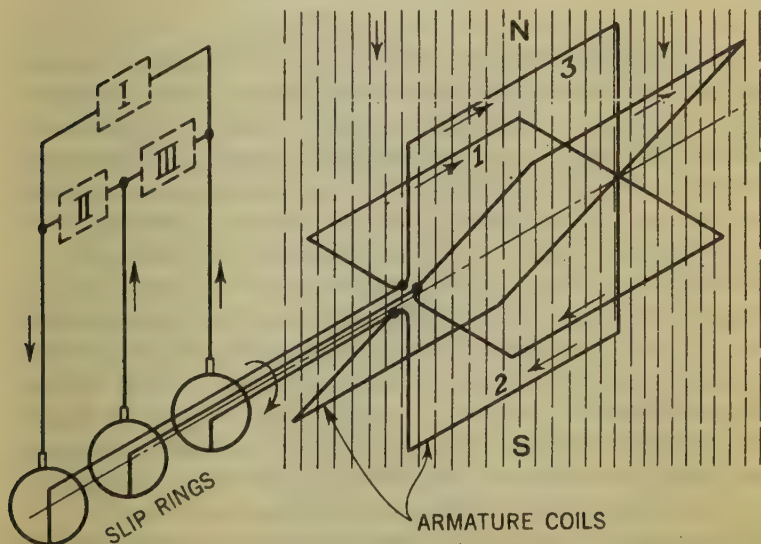


FIG. 24.—In commercial machines, it is customary to connect the loops or coils together as shown, since by doing this, only three slip rings are required. Thus each slip ring will serve two outside circuits.

and the number of poles in the motor. The equation for the speed is:

$$\text{Revolutions per minute} = \frac{\text{Frequency} \times 60}{\text{Number of pairs of poles}}$$

Since a synchronous motor runs at exactly this speed, it is a relatively simple matter to calculate the speed of any motor provided that the number of poles and the frequency of the source be known. Thus for example, an eight pole synchronous motor operating from a 60 cycle source, has an

$$r.p.m. = \frac{60 \times 60}{4} \text{ or } 900.$$

The Revolving Magnetic Field.—In the diagrams studied thus far, the poles making up the magnetic field have been stationary on the frame of the machine, and the armature in which the voltages are produced has rotated. This arrangement is universally employed in direct current machines, but alternating current motors and generators generally have revolving fields because of the need for only two slip rings.

When the revolving field construction is employed, the two slip rings need only carry the low voltage exciting current to the field. For a three-phase machine at least three slip rings would be required for the armature current which is often of high voltage and would, therefore, require a large amount of insulation, adding to the cost of construction, if a rotating armature were used. A schematic diagram of a single-phase alternating current generator with revolving field is shown in fig. 25.

Practically all polyphase alternating current motors depend for their operation upon a *revolving magnetic field* which pulls around with it the rotating part of the motor.

To produce a revolving field we will assume that two alternating currents of the same frequency and potential but differing in phase by 90 degrees, are at our disposal. We will now connect them to two sets of coils wound on the inwardly projecting poles of a circular iron ring, as illustrated in figs. 26 to 29.

It will be noted that when the current in phase 1 is at a maximum, fig. 30, the current in phase 2 is zero. The poles *A* and *A*₁ are magnetized, while the poles *B* and *B*₁ are demagnetized. The magnetic flux is in a direction from *N* to *S*, as indicated by the arrow, fig. 26.

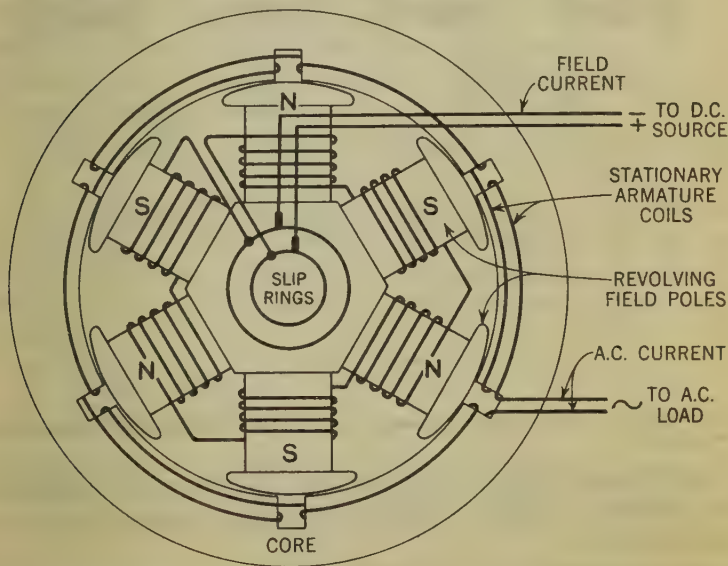
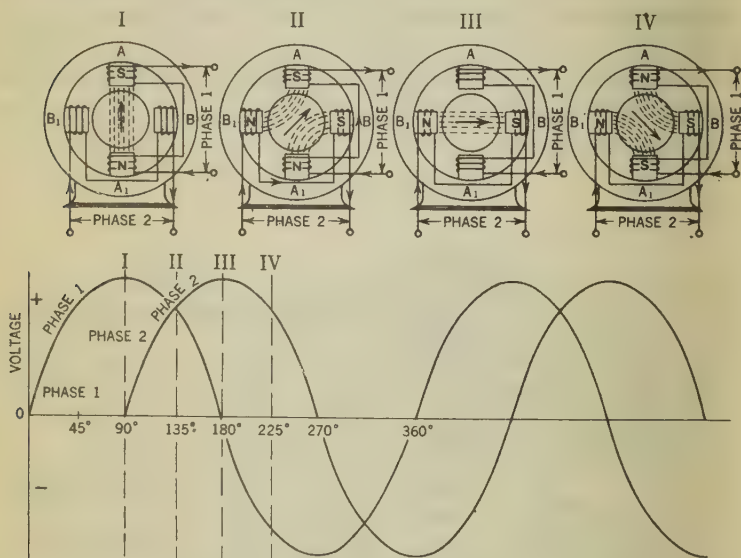


FIG. 25.—Showing construction methods of an alternating current generator, having the customary revolving field and six poles. If the generator shown be required to generate a 60-cycle current, the machine must be driven at a speed of exactly 1,200 revolutions per minute.

Now, referring to fig. 30, we find that one-eighth of a cycle (45°) later, the current in phase 1 has decreased to the same value as current in phase 2 has increased. The four poles are now equally magnetized, and the magnetic flux takes the direction of the arrow shown in fig. 27.



FIGS. 26 to 30.—Illustrating how a revolving magnetic field is produced by two currents 90 degrees apart.

Again, one-eighth of a cycle later, the current in phase 1 has dropped to zero, while the current in phase 2 is at its maximum.

With reference to fig. 28, this condition indicates that poles A and A₁ are demagnetized, but that the poles B and B₁ are magnetized, while the flux passes from N to S, as shown by the arrow.

Continuing our analysis, we observe that after an additional eighth of a cycle, the current in both phases 1 and 2 has decreased, and that the four poles are again equally magnetized and also that the magnetic flux is in the direction as indicated by arrow, fig. 29.

It will now readily be observed that if this process be continued at successive intervals during a complete period or cycle of change in the alternating current, the magnetic flux represented by the arrow will make a complete revolution for each cycle of the current.

This action of the current is inducing a *revolving magnetic field* because it would cause a magnet to revolve on its axis, according to the periodicity of the impressed alternating current. Since in our analysis only two phases have been chosen, it follows that we are dealing with a *two-phase* motor. The revolving magnetic field in a three-phase alternating current motor, with any number of poles, can be similarly obtained.

Other Polyphase Motors.—Although the synchronous motor is used commercially in certain applications, the *induction motor* is used much more extensively because of its simplicity. There are two principal classes of polyphase induction motors, namely:

1. Squirrel cage, and
2. Wound rotor type.

By definition, an *induction motor* is one in which the magnetic field in the rotor is induced by currents flowing in the stator. The rotor has no connections whatever to the supply line.

The Squirrel Cage Type.—This type of induction motor consists of a stator, which is identical to the armature of a

synchronous motor and has a "squirrel cage" rotor with bearings to support it. Because the stator receives the power from the line, it is often called the *primary* and the rotor the *secondary*.

In an induction motor of this type, the squirrel cage winding takes the place of the field in the synchronous motor. The squirrel cage, as shown in fig. 31, consists of a number of metal bars connected at each end to its supporting metal rings. As in the synchronous motor, a revolving field is set up by the currents in the armature.

As this field revolves, it cuts the squirrel cage conductors, and voltages are set up in them exactly as though the conductors were cutting the field in any other motor. These voltages cause current to flow in the squirrel cage circuit, through the bars under the north poles into the ring, back to the bars under the adjacent south poles, into the other end ring, and the circuit is completed back to the original bars under the north pole.

The current flowing in the squirrel cage, down one group of bars and back in the adjacent group makes a loop which establishes magnetic fields in the rotor core with north and south poles. This loop consists of one turn, but there are several conductors in parallel and the currents may be large. These poles in the rotor, attracted by the poles of the revolving field, set up the currents in the armature winding, and follow them around in a manner similar to that in which the field poles follow the armature poles in a synchronous motor.

There is, however, one very interesting and important difference between the synchronous motor and the induction motor; the rotor of the latter does not rotate as fast as the rotating field in the armature. If the squirrel cage were to go as fast as the rotating field, the conductors in it would be standing still with respect to the rotating field rather than cutting

across it. Then there could be no voltage induced in the squirrel cage, no currents in it, no magnetic poles set up in the rotor, and no attraction between it and the rotating field in the stator. The rotor revolves just enough slower than the revolving field in the stator to allow the rotor conductors to cut the revolving magnetic field as it slips by, and thus induces the necessary currents in the rotor windings.

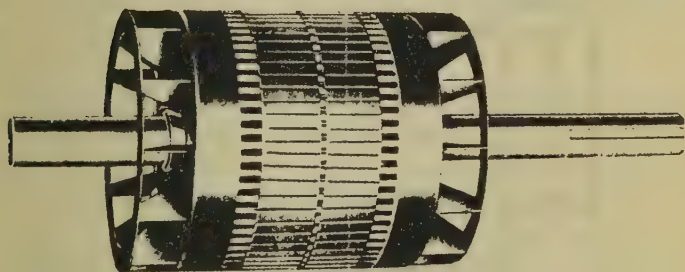


FIG. 31.—Showing a typical polyphase squirrel cage rotor with blowers.

Hence, the motor can never go quite so fast as the revolving field, but is always slipping back, and this difference in speed is called the “*slip*.” The greater the load, the greater the slip will be; that is, the slower the motor will run, but even at full load, the slip is not very great. In fact this motor is commonly considered to be a constant-speed motor.

The various classes of squirrel cage motors, their operation and control are given in a later chapter.

The Wound Rotor Motor.—This type of induction motor differs from the squirrel cage type in that instead of having a series of conducting bars placed in the rotor, it has a wire coil winding in it.

These insulated coils are grouped to form definite polar areas having the same number of poles as the stator. The rotor windings are brought out to slip rings whose brushes are connected to variable external resistances.

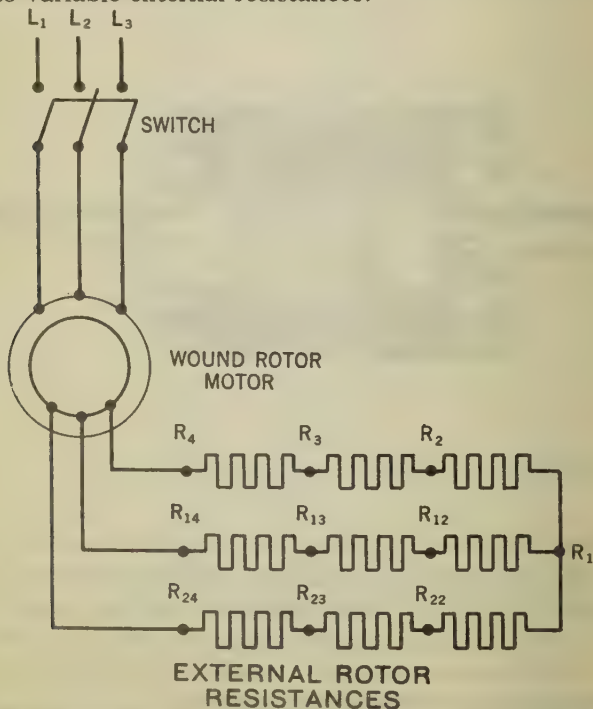


FIG. 32.—Wiring diagram showing connections between slip rings and external resistances in a wound rotor motor. The tapped connections are in this case brought out to a drum controller where the direction of drum rotation determines the amount of resistance in the circuit, and thus the speed of the motor.

By inserting external resistance in the rotor circuit when starting, a high torque can be developed with a comparatively low starting current.

As the motor accelerates up to speed the resistance is gradually reduced until at full speed the rotor is short circuited. By varying the resistance in the rotor circuit the motor speed can be regulated within practical limits.

This method of speed control is well suited for the wound rotor motor because it is already equipped with a starting resistance in each phase of the rotor circuit. By making these resistances of large enough current capacity to prevent dangerous heating in continuous service, the same resistances serve also for regulation of the speed.

Although effective speed control is best secured by the use of direct current motors, the wound rotor motor because of its adjustable rotor resistance, possesses one of the few methods of speed control available for alternating current motors.

Slip.—In a synchronous motor the speed is constant for any given frequency and number of poles in the motor.

In an induction motor, however, this exact relationship does not exist, but the rotor slows down a certain small amount when the load is applied.

The ratio of the speed of the field relative to the rotor, to synchronous speed is termed the *slip*. It is usually written:

$$s = \frac{N_s - N}{N_s}$$

Where s = slip (usually expressed as a percentage of synchronous speed).

N_s = Synchronous speed.

N = Actual rotor speed.

For example, a 6-pole, 60-cycle motor would have a synchronous speed of 1,200 *r.p.m.* If its rotor speed were 1,164 *r.p.m.*, the slip

$$s = \frac{1,200 - 1,164}{1,200} = 0.03 \text{ or } 3\%$$

The reversal of direction of rotation in any three-phase motor is accomplished by exchanging any two leads.

Single Phase Induction Motors

Single phase induction motors may be divided into two principal classes, namely:

1. Split-phase, and
2. Commutator motors.

Split phase type motors are subdivided into *resistance-start*, *reactor-start*, permanently *split-capacitor* and *capacitor-start* motors. The commutator type motors are subdivided into two groups, *series* and *repulsion* and each of these into several types and combination of types.

These two classes and subdivisions represent various electrical modifications of single phase induction motors, some one of which must be used to produce the necessary starting torque.

There are four principal methods used to provide the starting torque in a split-phase induction motor. All methods serve to increase the phase angle between the main winding and the starting winding, so as to produce a revolving magnetic field similar to that in a two-phase motor.

The Resistance-Start Motor.—This is a form of split-phase motor having a resistance connected in series with the starting (sometimes called auxiliary) winding. A schematic diagram

of this type of motor may be represented as in fig. 33.

Here a resistance is connected in series with the starting winding. This causes the starting winding to get strong first, then the main winding gets strong, giving a two-phase rotating field effect for starting.

When the motor reaches approximately 75% of its rated speed, a centrifugal switch opens to disconnect the starting-winding from the line. This motor is known as the *resistance*

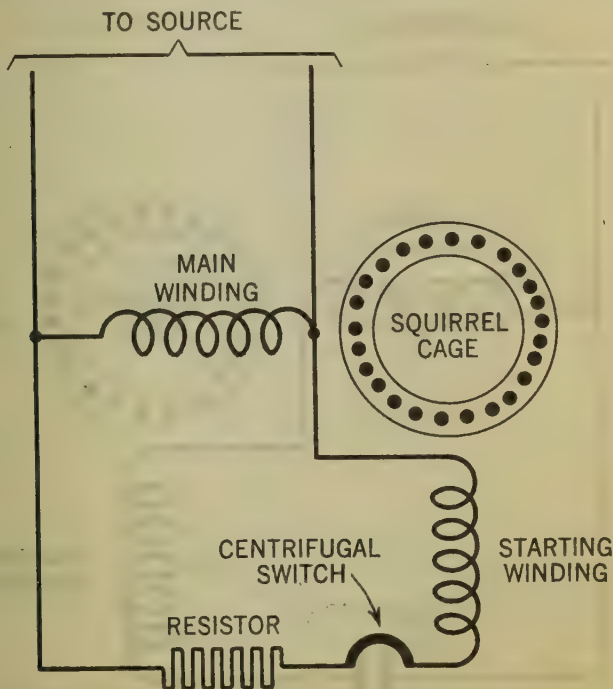


FIG. 33.—Schematic diagram showing the winding arrangement in a resistance-start, split-phase, induction motor. Although in most motors of this type, the starting winding is made inoperative by means of a centrifugally operated switch, other starting switches operate on the thermal principle.

start, split-phase motor, and is commonly used on washing machines. It is not practical to build such motors for the heaviest types of starting duty.

The Permanently Split-Capacitor Motor.—In this motor, fig. 34, two stationary windings are connected to a single phase line with a squirrel cage rotor.

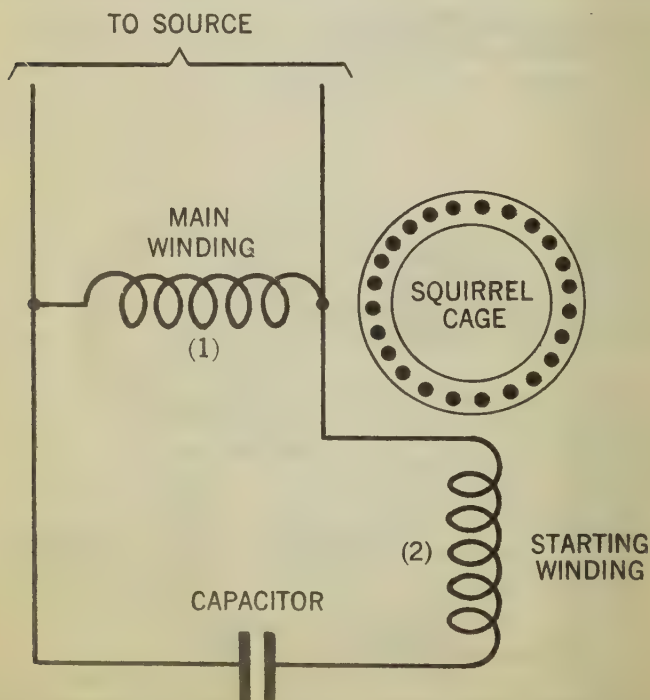


FIG. 34.—Diagram giving the winding connections in a permanently split capacitor motor.

The capacitor has the peculiar characteristic of making coil 2 magnetically strong earlier than coil 1. Thus, we have coil 2 strong first, then coil 1 and then coil 2 again. This is the same as the two-phase motor discussed previously, and we have the rotating field effect which rotates the squirrel cage rotor. As the capacitor is here mounted permanently in the circuit, this motor is known as the permanently split-capacitor

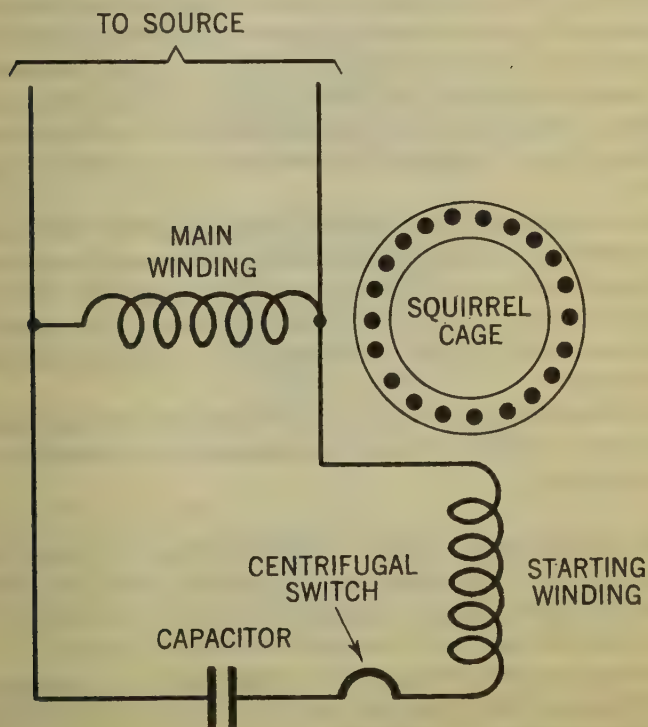


FIG. 35.—Showing winding connections in a capacitor motor.

motor. It is employed chiefly on small fans. Because capacitors for continuous duty are expensive and somewhat bulky, it is not practical to make this motor for heavy duty starting.

The Capacitor-Start Motor.—In applications where a high starting torque is required, a motor as shown in fig. 35 is employed. This is but another form of split-phase motor having a capacitor or condenser connected in series with the starting-winding. The construction is similar to the permanently split-capacitor motor, but differs mainly in that the starting-winding is disconnected at approximately 75% of rated speed by a centrifugal switch as in the case of the resistance-start motor.

The centrifugal switch is mounted on the motor shaft and as the name implies, works on the centrifugal principle and acts to disconnect the starting-winding when the speed at which the switch is set is reached, as previously noted. The capacitor-start motor has a greater starting ability than the resistance-start motor.

As the capacitor is only in use during the starting period a high capacity can be obtained economically by selecting it for this short duty.

The Shaded-Pole Motor.—Another type of single phase induction motor is schematically represented in fig. 36. Principally this motor consists of a squirrel cage rotor and two or more coils with an iron core to increase the magnetic effect.

Part of one end of this core is surrounded by a heavy copper loop known as the "*shading ring*." This ring has the characteristics of delaying the flow of magnetism through it. With alternating current applied to the coil, the magnetism is strong

first at *A*, and then slightly later at *B*. This gives a rotating field effect that causes the rotation of the squirrel cage in the direction in which the shading ring points. A motor thus constructed is known as a *shaded pole motor*.

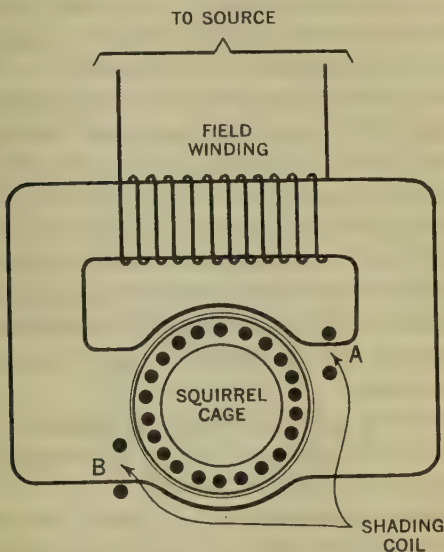


FIG. 36.—Illustrating arrangement of windings in a skeleton-type shaded pole motor.

Because of the limitations of force and current possible in shading poles, it is not feasible to build efficient motors of this type larger than approximately $1/20$ *h.p.* It has found its use principally on small fans, agitators and timing devices.

The Repulsion-Start Induction Motor.—These are operated in various ways. In the running position the brushes may or may not be raised. If the same rotor winding be used for

starting and running, the commutator is short circuited at about 75% of rated speed to obtain a rotor winding approximating the squirrel cage in its functioning.

Other designs have two rotor windings, that is, a *squirrel cage* and a *wound winding* for running and starting respectively. In this type no rotor mechanism is required as the magnetic conditions automatically transfer the burden from one winding to the other as the motor comes up to speed.

The repulsion starting may best be explained by the action of a wire charged by a battery and moved across the face of a magnet. Here there is a force on the wire which, for example, tends to move the straight piece of wire upward or downward, depending upon the direction of the current flowing.

In this way it can be demonstrated that a current carrying wire, in a magnetic field, has a force in it tending to move it in a certain direction. Also, that if the direction of the current flowing through the wire be reversed, the force and motion are in opposite directions.

Repulsion starting operates on this principle. Current is caused to flow in the wires of the rotor winding and these wires are affected by a magnetic field.

Fig. 37 illustrates a stationary “C” shaped iron core on which is mounted a coil connected to a single-phase supply line. In the opening of the “C” is a ring of iron on which is wound a continuous uniform coil. The path of the magnetism, produced by the first coil, is around through the “C” shaped core and then, dividing equally, half of the magnetism passes through each half of the iron ring.

The winding and the magnetism are identical in both halves of the ring. Thus any effect which the magnetism may have on the winding between *E* and *G* should be the same as that produced in the winding *E* and *H*. By test, connecting *G* and *H* together through an ammeter, it can be demonstrated that this

is true as no current flows when a wire is connected between *G* and *H*. By further similar tests it can be shown that the maximum current will flow when a wire is connected between *E* and *F*. Thus the first requirement of our principle has been satisfied—with a wire connecting *E* and *F* there is current flowing in the rotor winding.

Assume that the current flows upward in this wire from *F* to *E*. At point *E* it divides equally, half going to the winding to the left of *E*, and the other half to the right. Referring to the wires on the outer surface of the ring, those on the right have the current flowing towards the observer while those on the left have the current flowing away from him. Thus the magnetic field from the "C" shaped core tends to force the wires on the right in one direction and those on the left in the other direction. The forces are equal and opposite so that they neutralize each other and no motion takes place.

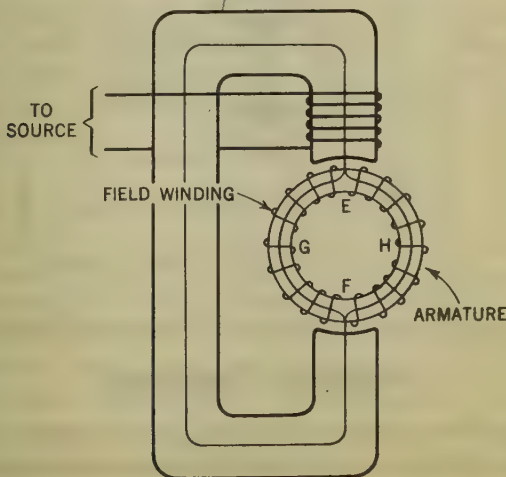


FIG. 37.—Illustrating principles of a repulsion-start induction motor.

Therefore, it is necessary to add a magnetic field that can effectively react with the current in the rotor winding. This is readily done by adding another "C" shaped core with its own coil, as shown in fig. 38. The rotor winding current under each tip of this "C" shaped core is all in the same direction and rotation is obtained. The wire from *E* to *F* in fig. 37 has been replaced with stationary brushes so that it continued to maintain this connection as the rotor turns.

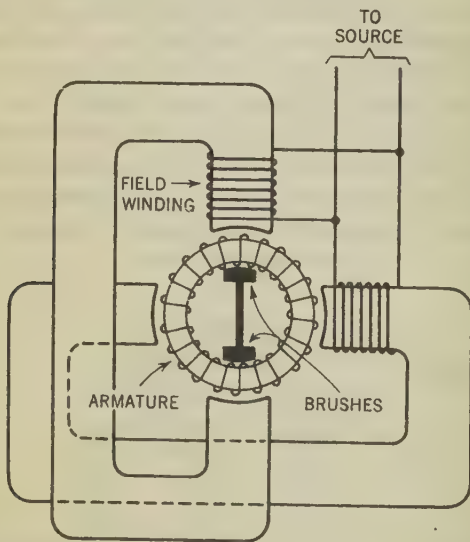


FIG. 38.—Schematic arrangement of windings in a repulsion-start induction motor.

Motor Control

Although the function of motor control is fully covered in subsequent chapters, a brief outline of its essentials will be of aid in our further study of various types of motors and associated control circuits.

The elementary functions of control are: *starting, stopping* and *reversing* the motor. These, however, are only a few of the many contributions which the control renders to efficient operation of industrial motors.

The most common control functions of industrial motors are:

1. To limit torque on the motor and machine.
2. To limit motor starting current.
3. To protect motor from overheating.
4. To stop the motor quickly.
5. To regulate speed.
6. Miscellaneous functions.

Limiting of Torque.—One example on the need for limiting of torque is that of a belt driven motor operated machine throwing the belt when the motor is started. The pulleys may be correctly lined up, and the belt tension may be correct, yet the belt is thrown off in starting. This is the result of applying torque too quickly at standstill, and can be avoided by limiting the torque on the motor in starting. As another example, the blades on centrifugal fans can be sheared off if too much torque is applied to the fan in starting.

Limiting of Starting Current.—It is a common sight to see direct current motors flash over at the commutator when too much current is applied to the motor in bringing it up to speed. Also, it is common to see lights blink when a motor on the same power circuit is started. True, this blinking of lights can often be reduced by selecting a motor with the right characteristics, but usually the real solution is the selection of a control that limits the starting current, either by inserting resistance in the circuit or by using a reduced voltage source of power.

Protection from Overheating.—Motors are designed to produce full load torque for a definite period without overheating. While the motor is capable of exceeding its normal output for limited periods, there is nothing inherent in the motor to keep its temperature within safe limits. It is, therefore, the function of the control to prevent the motor from overheating excessively, without shutting it down unnecessarily.

Quick Stopping.—Where a driven machine has high inertia, it will continue to run for a considerable time after the power has been disconnected. There are several types of control, such as electric brakes, to stop a motor quickly; the one most generally used on alternating current motors is the plugging switch. To plug a motor, it is necessary only to disconnect it from the line, then reconnect it so that the power applied to the motor tends to drive it in the opposite direction. This brakes the motor rapidly to a standstill, at which time the reverse power is cut off by the plugging switch.

Speed Regulation.—Fans are sometimes run at various speeds, depending upon the ventilation requirements. For some applications, it is advisable to use a two-speed motor; but where a greater variety of speeds are required, a motor with variable speed control may be the best solution to the problem.

Miscellaneous Control Functions.—Adequate control equipment covers various other protective functions which are not as common as those enumerated previously. Among these are reverse phase protection, which prevents a motor from running in the wrong direction if a phase is inadvertently reversed; open phase protection, which prevents the motor from running on single phase in case a fuse blows; and undervoltage protection, which prevents a motor from starting after a power failure, unless it is started by the operator.

CHAPTER 2

Wiring Diagrams

Purpose of Diagrammatical Representation.—The purpose of any wiring diagram is to indicate electric circuits by means of conventional symbols, thus making it possible to connect the various apparatus and instruments in diagrammatic form, from which actual connections in the field may be made.

Wiring diagrams in addition serves to make a permanent record of the wiring and apparatus installed, thus facilitating changes and replacement, and also assists in the location of any trouble that may develop in the circuit after installation.

Large manufacturers of electrical equipment usually employ numerous engineers whose duty consists in designing circuits varying in complicity from simple metering circuits to complete automatic control circuits of large industrial motors and generators.

Diagram Design Procedure.—The general procedure in circuit or diagram design of a more complicated nature usually consists in working out an elementary or schematic diagram first, then from this layout the working or general diagram.

In the elementary diagram no attention need be paid to the physical location of contactors or coils, but the strictest attention is directed toward the electrical sequence of operation and to see that the equipment is correctly connected for its proper operation.

After a careful check of the elementary diagram has been made the circuit is usually transferred to a working diagram where the relays, contactors and other apparatus are laid out in a rear-view order, although the actual electrical connections conform in every detail with that of the elementary diagram. Thus, the purpose of the elementary diagram is only to simplify the circuit for construction and checking.

Various Forms of Diagrams.—In addition to the aforementioned there are several other forms of diagrams, each designed for a particular purpose or installation. The *National Electrical Manufacturers Association* (NEMA) and *American Institute of Engineers* (AIEE) have made the following definitions:

Controller Wiring Diagram.—A controller wiring diagram is a diagram showing the electric connections between the parts comprising the controller, indicating the external connections.

External Controller Wiring Diagram.—An external controller wiring diagram is a diagram showing the electric connections between the controller terminals and outside points, such as connections from the line to the motor, and to auxiliary devices.

Controller Construction Diagram.—A controller construction diagram is a diagram indicating the physical arrangement of parts such as wiring, busses, resistor units, etc.

Example.—A diagram showing the arrangement of grids and terminals in a grid type resistor.

Elementary Controller Wiring Diagram.—An elementary controller wiring diagram is a diagram using symbols, and a plan of connections to illustrate in simple form the scheme of control.

Control Sequence Table.—A control sequence table is a tabulation of the connections which are made for each successive position of the controller.

How to Read Wiring Diagrams.—As already mentioned, since wiring diagrams are represented by symbols, it is of the utmost importance that these be thoroughly understood. These basic symbols, which have been generally adopted by electric equipment manufacturers, are shown on pages 63 to 72.

A study and understanding of these symbols by engineers, wiremen, maintenance men, operators and others who work on wiring diagrams will result in a saving of time and energy when determining how control equipment should be installed and how it is intended to operate. A knowledge of the symbols will make it easy to identify the devices and apparatus represented on the print, even though there may be little resemblance between the symbol used and the actual appearance of the device.

It is usual practice for a diagram to show devices in their de-energized position. The power and main motor circuits are indicated by heavy lines, and the control circuits are indicated by light lines.

Fig. 1 illustrates the connections of a typical A.C. reversing magnetic switch, push-button station and induction motor.

The magnetic switch shown contains two three-pole contactors and a temperature overload relay. Each contactor has three normally open power contacts, a normally open electric

interlock, and an operating coil. The relay includes two heaters connected in the power circuit and a normally closed control-circuit contact. The complete symbol for the switch shows its electric parts in the same general relationship as they appear on the actual device.

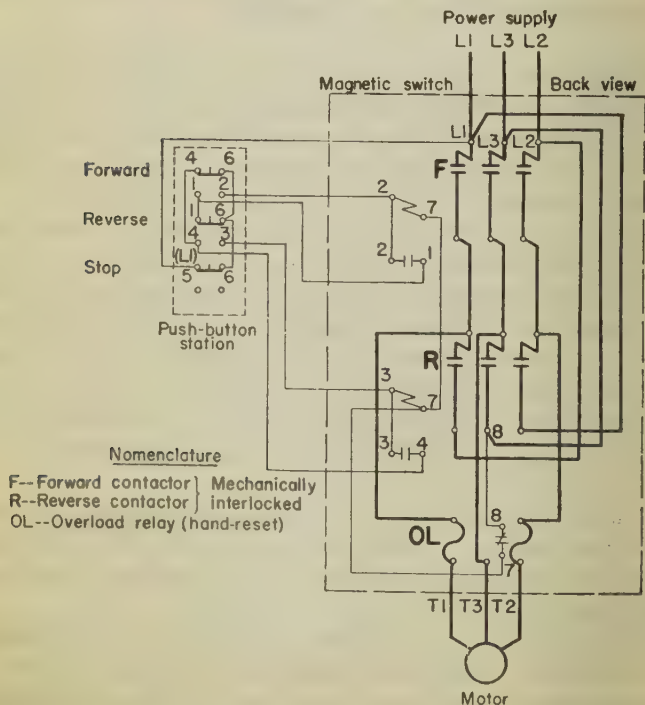


FIG. 1.—Wiring diagram of reversing magnetic switch.

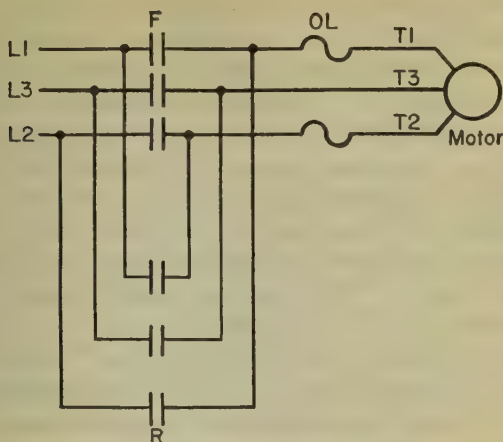


FIG. 2.—Elementary diagram of power circuit shown in fig. 1.

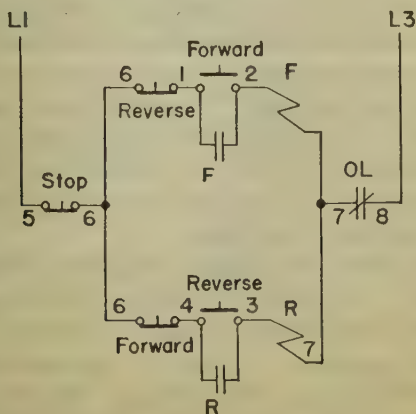


FIG. 3.—Elementary diagram of control circuit shown in fig. 1.

When the *forward* button is depressed (see fig. 1) contactor *F* closes and applies power to the motor. A holding circuit for the coil of *F* is established around the *forward* push-button by auxiliary interlock *F*. The motor continues to run until shut down by depressing the *stop* button, by the tripping of the overload relay, or by power failure. Following an overload condition which causes relay *OL* to trip it is necessary to reset the relay contact by hand before the motor can be restarted. Operation of the motor in the reverse direction is obtained from the *reverse* button. The back or normally closed contacts of the directional push-button units are used for electric interlocking and prevent the coils of contactors *F* and *R* from being energized at the same time. With this arrangement it is also possible to reverse the motor direct from the *forward* and *reverse* buttons without first operating the *stop* button.

To understand the operation of control equipment it is necessary to have a complete idea of the circuits involved. As control systems and circuits become more complicated and require more devices it is increasingly difficult to check the circuits and understand the operation from the conventional panel type of wiring diagram. For this reason elementary or schematic diagrams are used. Since the main reason for this type of diagram is simplicity the various electric elements of devices are separated. They are shown in their respective functional position in the circuit without regard to their actual physical relationship on the device.

It is also customary to separate the power circuits from the control circuits. Elementary diagrams which are often referred to as one-line diagrams, make it easy to visualize and understand the operation. They are particularly beneficial when trouble-shooting or when changes become necessary in the operation. For example, in some cases when large equip-

ments are involved the elementary circuits are shown on one print, and the detailed panel wiring and inter-connections by separate prints. In other cases the circuits may be shown in both elementary and detailed forms on a single print.

An elementary diagram of the magnetic switch shown in fig. 1 is illustrated in figs. 2 and 3.

In controllers of the magnetic switch type just described the motor power circuits are handled by magnetically-operated contactors under the control of a push-button station or other auxiliary device. In contrast to this type, there are different kinds of controllers which are manually operated. In these the contacts which carry the main motor circuits are closed and opened by hand. Fig. 4 illustrates the connections of a manual drum switch of the cam type for use with a series-wound, direct-current motor.

Here the contacts of the cam switch are indicated as shown by the symbol in fig. 5a. The letter *X* in fig. 4 indicates that the contacts close on the handle position thus shown.

Auxiliary control contacts *UV*, *LSF* and *LSR* which are closed at the off position are represented by the symbol shown in fig. 5b.

When the switch handle is moved to its first point *forward*, contacts *1F*, *2F* and *M* close and apply power to the motor. As the handle is notched over to its fourth position contacts *1A*, *2A* and *3A* close to short circuit the starting resistance.

Returning the handle to its off position causes the previously mentioned contacts to open and disconnect the motor from the line. When the handle is moved to the *reverse* position, contacts *1R*, *2R* and *M* close to energize the motor in the reverse direction.

In fig. 4 are shown two control type limit switches. In their closed position, the contacts of these switches are illus-

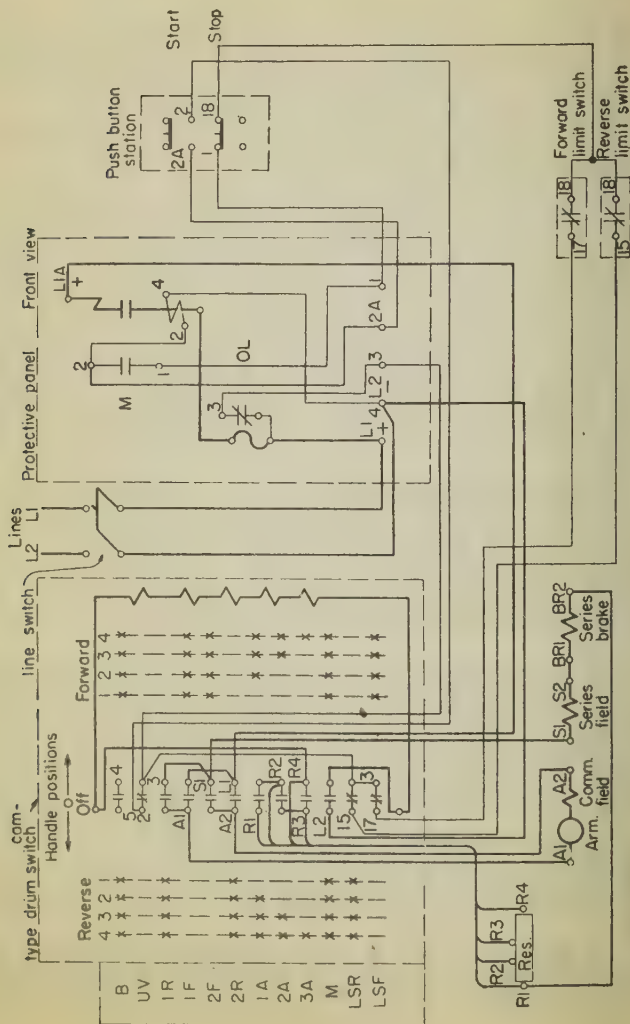
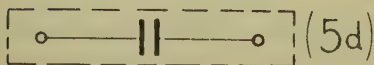
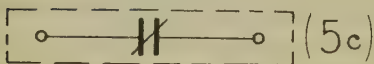


FIG. 4.—Wiring diagram of cam-type drum switch with protective panel and overtravel limit switches.

trated by a symbol shown in fig. 5c. These contacts assume a normal open position as shown by the symbol fig. 5d, when the switches are tripped at their respective ends of travel.

The connections in fig. 4 show not only the circuits of a manual cam-type drum switch, but also how under-voltage, overload and directional overtravel protection can be obtained by the use of a protective panel, a push-button station, and control type limit switches.



FIGS. 5a to 5d.—Symbols for various contact switches shown in fig. 4.

Abbreviations Used.—Devices such as relays, contactors and switches, etc., for use on diagrams in connection with symbols are usually marked to indicate the function or use of the particular device.

The following abbreviations are used for device markings and designated as standards by *National Electrical Manufacturers Association* (NEMA):

Armature accelerator	A
Armature shunt	AS
Auxiliary switch (breaker) normally open	"a"
Auxiliary switch (breaker) normally closed	"b"
Balanced voltage	BV
Brake	BR
Compensator—running	MR
Compensator—starting	MS
Control	CR
Door switch	DS
Down	D
Dynamic Braking	DB
Field accelerator	FA
Field decelerator	FD
Field discharge	FD
Field dynamic brake	DF
Field failure (loss of field)	FL
Field forcing (decreasing on variable voltage)	DF
Field forcing (increasing on variable voltage)	CF
Field protective (field weakened at standstill)	FP
Field reversing	FR
Field weakening	FW
Final limit—forward	FLF
Final limit—reverse	FLR
Final limit—hoist	FLH
Final limit—lower	FLL
Final limit—up	FLU
Final limit—down	FLD
Forward	F
Full field	FF
Generator field	GF
High speed	HS
Hoist	H
Jam	J

Kick off	KO
Landing	LD
Limit switch	LS
Lowering	LT
Low speed	LS
Low torque	LT
Low voltage	LV
Main or line	M
Master switch	MS
Maximum torque	MT
Middle landing	MLD
Motor field	MF
Overload	OL
Pilot motor	PM
Plug	P
Reverse	R
Series relay	SR
Slow down	SD
Thermostat	TS
Time	T
Up	U
Undervoltage	UV
Voltage relay	VR

Terminal Markings

General.—The purpose of applying markings to the terminals of electric power apparatus according to a *Standard* is to aid in making up connections to other parts of the electric power system and to avoid improper connections that may result in unsatisfactory operation or damage.

Location of Markings.—The markings are placed on, or directly adjacent to, terminals to which connection must be made from outside circuits or from auxiliary devices which must be disconnected for shipment. They are not intended to be used for internal machine connections.

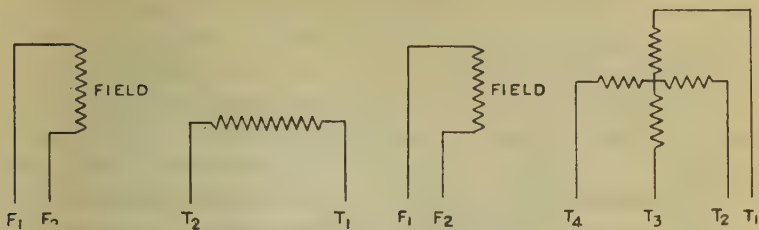
Precautions.—Although the system of terminal markings with letters and subscript numbers gives information, facilitating the connections of electrical machinery, there is the possibility of finding the terminals marked without system or according to some system other than standard (especially on old machinery or machinery of foreign manufacture). There is a further possibility that internal connections have been changed or that errors were made in markings. It is advisable before connection of apparatus to power supply systems to make a check test for phase rotation, phase relation, polarity and equality of potential.

Markings.—The markings consist of a capital letter of the alphabet followed by a subscript numeral (Arabic).

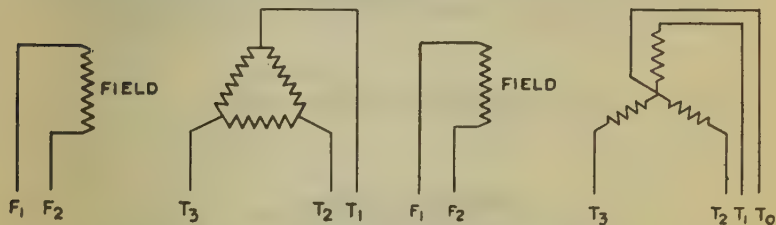
Significance of the Terminal Letter.—The letter indicates the character or function of the winding which is brought to the terminal. The terminal letters assigned to the different types of windings or their functions will be found on pages 51 to 57.

Significance of the Subscript Numerals.—(a) *Subscript 0 (Zero).*—A terminal letter followed by the subscript numeral 0 designates a neutral connection. Thus T_0 would be applied to the terminal on connection from neutral point of a stator winding.

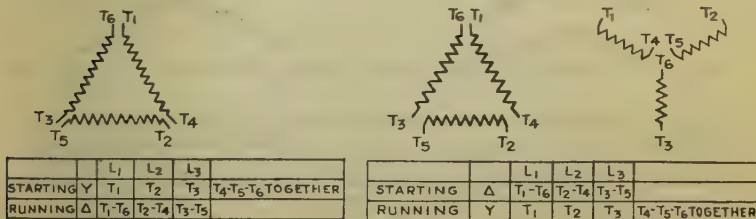
(b) *Subscript Numerals on Alternating Current Machine Terminals.*—The subscript numerals 1, 2, 3, etc., indicate the order of the phase succession for standard direction of rotation. This standard direction of rotation for alternating current generators and synchronous motors is clockwise when facing the end of machine opposite drive. (It is customary to connect up the coil windings and place collector rings on this end.)



Figs. 6 and 7.—Illustrating terminal markings for A.C. generators and synchronous motors single- and two-phase, respectively.



Figs. 8 and 9.—Illustrating terminal markings for A.C. generators and synchronous motors, three-phase delta and star, respectively.



Figs. 10 and 11.—Induction motors, stator connections. With the winding arrangement shown in fig. 10, the starting of the motor takes place with the winding connected in star, and the running in delta. Fig. 11 indicates a motor for starting in delta and running in star.

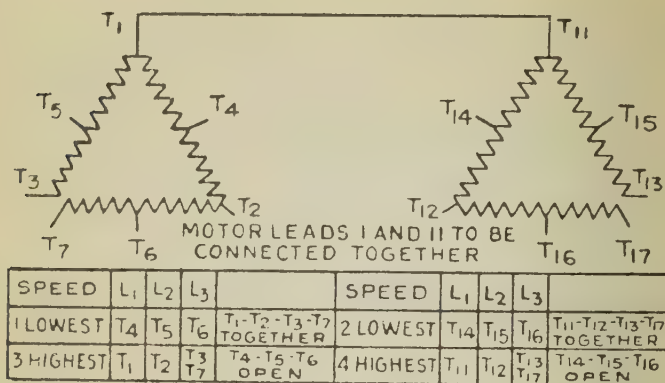


FIG. 12.—Induction motor stator connections, three-phase, four-speed.

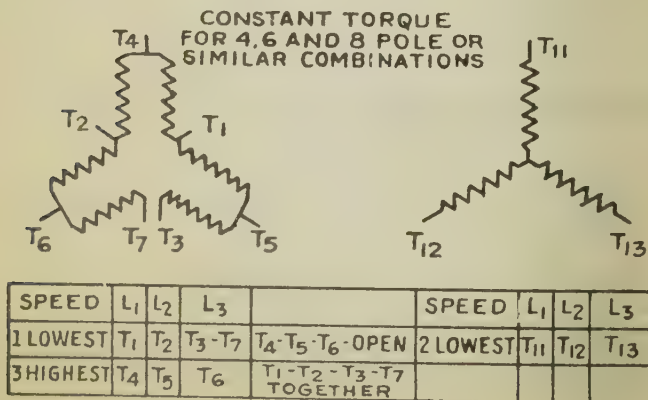
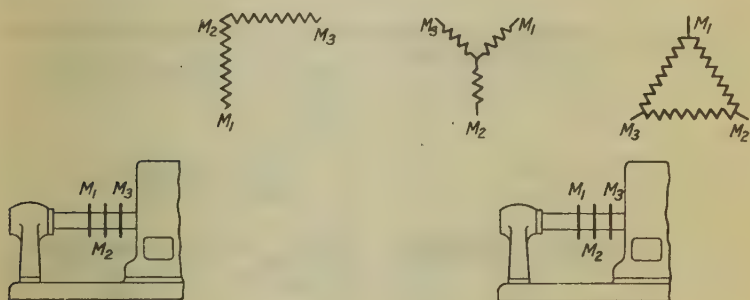


FIG. 13.—Induction motor stator connection, three-phase, three-speed.

For induction motors the subscript numerals 1, 2, 3, etc., indicate the order of the succession of the phases. Thus, if induction motor terminals T_1 , T_2 , T_3 are respectively connected to alternating current generator terminals T_1 , T_2 , T_3 , the generator will cause the induction motor to turn in the same direction. In a synchronous converter the sequence of the subscript numerals 1, 2, 3 applied to the collector ring leads M_1 , M_2 , M_3 indicate that when the collector leads are connected to correspondingly numbered terminals of a three-phase generator, standard rotation of the generator (clockwise facing end opposite drive) will cause direction of rotation, which is clockwise when viewing the direct-current or commutator end.

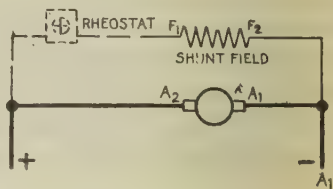
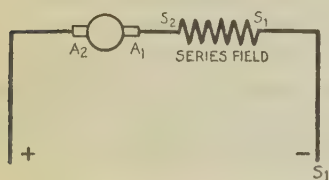


FIGS. 14 and 15.—Induction motors, rotor connections, two- and three-phase, respectively.

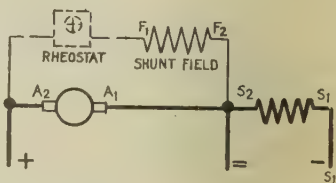
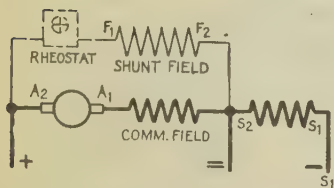
(c) *Subscript Numerals on Direct Current Machine Terminals.*

As applied to the terminals of direct current windings of generators, motors and synchronous converters, the subscript numerals indicate the direction of current-flow in the windings. Thus, with standard direction of rotation and polarity, the current in all windings will be flowing from 1 to 2, or from a lower to a higher sub-number; for example, 3 to 4, etc.

The standard direction of rotation for direct current generators is clockwise when facing the end of machine opposite drive (usually the commutator end of the machine). The standard rotation for direct current motors is counter-clockwise when facing end opposite drive (usually the commutator end).



FIGS. 16 and 17.—Illustrating standard terminal markings on D.C. series and shunt generator, respectively, without commutating poles.

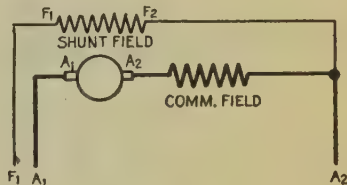
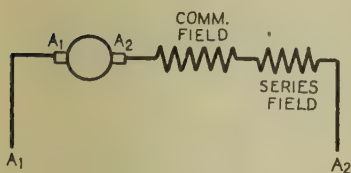


FIGS. 18 and 19.—Illustrating standard terminal markings on D.C. compound generators with and without commutating poles.

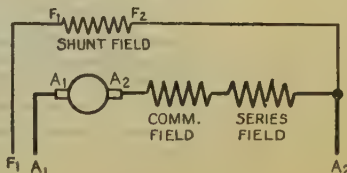
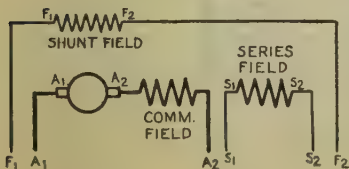
Note 1.—Any direct current machine can be used either as a generator or as a motor. For desired direction of rotation, connection changes may be necessary. The conventions for current flow in combination with the standardization of opposite directions of rotation for direct current generators and direct current motors works out so that any direct current machine can be called “generator” or “motor” without change in terminal markings.

Note 2.—A direct current motor and a direct current generator, by direct coupling, constitute a “motor generator.” With such coupling, direction of rotation of motor and generator are necessarily reversed when each is viewed from the “end opposite drive.” The standardized clockwise rotation for direct current generators and counter-clockwise for direct current motors meets such coupling requirements without change in standard connections or rotation for either direct current machine.

Similarly, a direct current motor may be coupled to an alternating current generator without changing from the standard for either individual machine. However, the coupling of an alternating current motor to a direct current generator cannot be made without rotation other than standard for one of the two machines. Since the rotation of the alternating current machine is usually the more simply changed, it is general practice to operate a motor generator with clockwise rotation viewed from generator end.

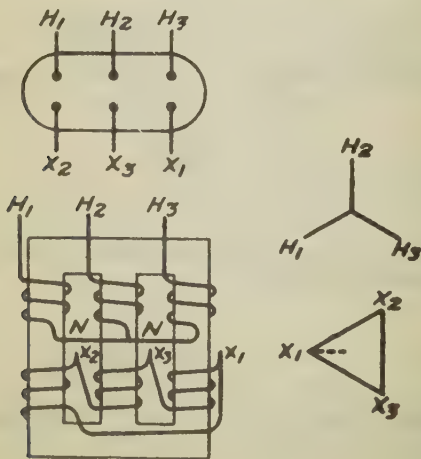


FIGS. 20 and 21.—Illustrating standard terminal markings on D.C. series and shunt motor of the non-reversing commutating pole type.

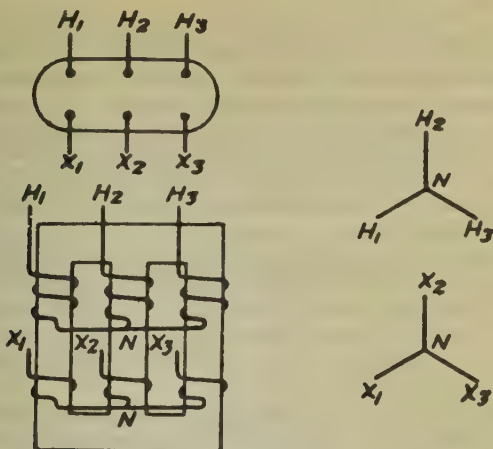


FIGS. 22 and 23.—Illustrating standard terminal markings on D.C. compound motors of the reversing and non-reversing commutating pole type, respectively.

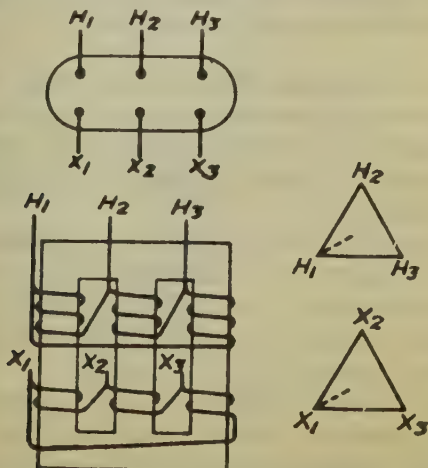
(d) *Subscript Numerals on Transformer Terminals.*—On single-phase transformers the subscript numerals indicate the polarity relation between terminals on primary and on secondary windings. Thus, during that part of the alternating current cycle when high tension terminal H_1 is positive (+) with respect to H_2 , the same part of the cycle the low tension terminal X_1 is positive with respect to X_2 . The idea is further carried out on single-phase transformers having tapped windings by so applying to the taps the subscripts 1, 2, 3, 4, 5, etc., that the potential gradient follows the sequence of the subscript numerals.



Figs. 24 to 27.—Showing standard terminal markings for a star-delta connected three-phase transformer having additive polarity, 30° angular displacement and standard-phase rotation.



FIGS. 28 to 31.—Showing standard terminal markings for a star-star connected three-phase transformer, having subtractive polarity, zero phase displacement and standard-phase rotation.



FIGS. 32 to 35.—Showing standard terminal markings for a delta-delta connected three-phase transformer, having subtractive polarity, zero-phase displacement, and standard-phase rotation.

Note 3.—When the primary of a transformer receives energy over the connecting leads the secondary delivers energy to its connected circuit; the direction of current flow in the winding is reversed with respect to the polarity of the pressure at the terminals. It is important to take note of the difference between the practice in applying subscript numerals to direct current generators and motors where the subscript numbers are assigned according to direction of current flow, and to the case of single-phase transformers where subscript numbers are assigned according to terminal pressure.

In the case of polyphase transformers, the terminal subscript numbers are so applied that if the phase sequence of voltage on the high voltage side is in the time order H_1, H_2, H_3 , etc., it is in the time order X_1, X_2, X_3 , etc., on the low voltage side and also in the time order Y_1, Y_2, Y_3 , etc., if there is a tertiary winding. For further details of transformer connections see pages 625 to 658.

Note 4.—The terminal marking of polyphase transformers affords information on how phase rotation is carried through the transformer, but does not disclose completely the phase relations between correspondingly numbered primary and secondary terminals. Consequently, additional information on internal connections is required before polyphase transformers can safely be paralleled.

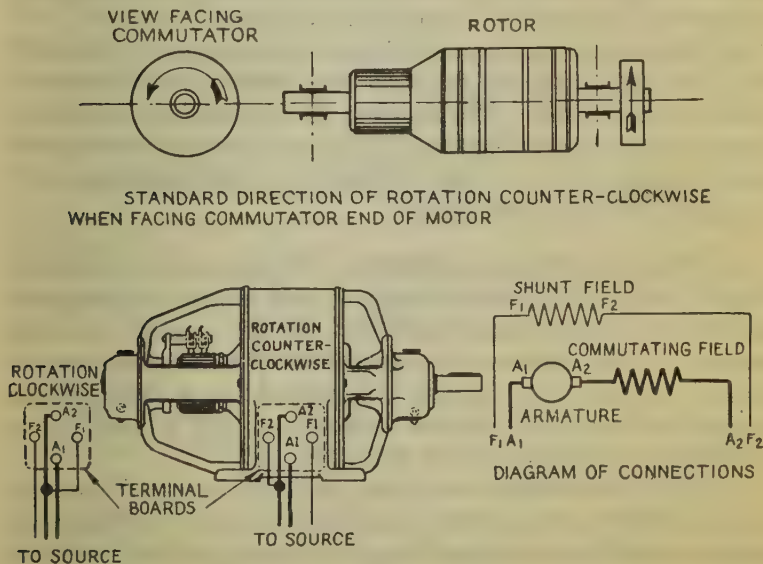
Reversals of Rotation, Polarity and Phase Sequence.—(a) Alternating current generators driven counter-clockwise (clockwise is standard) will generate without change in connections, but the phases will follow the sequence 3, 2, 1 instead of the sequence 1, 2, 3, etc.

(b) Synchronous motors, synchronous condensers, induction motors and synchronous converters may be operated with reversed rotation by so transposing connections that phase sequence of the polyphase supply is applied to the terminals in reversed order, that is, 3, 2, 1.

(c) Direct current generators with connections properly made up for standard rotation (clockwise) will not function if driven counter-clockwise, as any small current delivered by the armature tends to demagnetize the fields and thus prevent the armature from delivering current. If conditions call for re-

versed rotation, connections should be made up with either the armature leads transposed or the field leads transposed.

(d) The polarity of a direct current generator with accompanying direction of current flow in the several windings, is determined by the *N* and *S* polarity of the residual magnetism. Accident or special manipulations may reverse this magnetic polarity. Though the generator itself will function as well with either polarity, an unforeseen change may cause disturbance or damage when connected to other generators or devices.



Figs. 36 to 40.—Illustrations showing terminal markings and connections to a D.C. shunt motor. If it is desired to run the motor in a direction opposite to the standard counter-clockwise, i.e., clockwise, the field leads should be interchanged as shown on terminal block, fig. 38.

(e) Direction of rotation of direct current motors depends not on absolute polarity, but on a relative polarity between field and armature. As no dependence is placed on residual magnetism for determining the initial direction of rotation, it is not necessary when connecting up direct current motors to regard the polarity of the direct current supply connections. With standard direction of rotation, if current is found to be flowing from terminal 1 to 2 in one of the windings, it will be found in all the other windings as flowing from 1 to 2. But because of the disregard of polarity in connecting direct current motors, the current is as likely to be flowing from terminal 2 to terminal 1 in each of the several windings.

(f) Reversal of rotation of a direct current motor is obtained by a transposition of the two armature leads or by a transposition of the field leads. With such reversed rotation (clockwise), when polarity of supply makes direction of current in armature from terminal 2 to 1, it will be flowing in field windings from terminal 1 to 2 and vice versa.

(g) With synchronous converters, the practice of alternating current starting eliminates residual magnetism as the factor determining direct current polarity. Proper polarity for connection to other apparatus is secured either by separate excitation of the field or by special manipulation of a switch which permits the converter to reverse direct current polarity, thus correcting a start with wrong polarity.

(h) If a synchronous converter is to be operated with reversed direction of rotation (counter-clockwise, viewing commutator end) besides transposing alternating current terminal connections, it is also necessary, as in the case of the direct current generator, to make a transposition of armature leads or a transposition of field leads.

TABLE SHOWING TERMINAL LETTERS ASSIGNED TO
DIFFERENT TYPES OF WINDINGS AND THEIR FUNCTION

Description	Direct Current	Alternating Current
Brake	B_1, B_2, B_3 , etc.....	B_1, B_2, B_3 , etc.
Brush on Commutator (Armature)	A_1, A_2	A_1, A_2, A_3 , etc.
Brush on Slip Ring (Rotor) .....	.....	M_1, M_2, M_3 , etc.
Field (Commutating)	C_1, C_2 . Not usually marked on motors	.....
Field (Series)	S_1, S_2 .....	.....
Field (Shunt)	F_1, F_2	F_1, F_2
Line	L_1, L_2	L_1, L_2, L_3 , etc.
Neutral Connection	Terminal letter with subnumeral "0"	Terminal letter with subnumeral "0"
Resistance (Armature)	R_1, R_2, R_3 , etc.....	R_1, R_2, R_3 , etc.
Resistance (Shunt Field)	V_1, V_2, V_3 , etc.....	.....
Stator .....	.....	T_1, T_2, T_3 , etc.
Transformer (High-Voltage) .....	.....	H_1, H_2, H_3 , etc.
Transformer (Low-Voltage) .....	.....	X_1, X_2, X_3 , etc.
Transformer (Tertiary-Winding) .....	.....	Y_1, Y_2, Y_3 , etc.

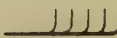
Wiring Symbols*.—The symbols used on wiring diagrams to represent various electrical devices such as contactors, relays and other apparatus are today standardized and simplified, thus facilitating not only the reading and understanding, but in addition facilitates the maintenance and installation of electrical equipment of all kinds.

*NOTE.—A complete set of standard electrical symbols for power, control and measurement is published by the *American Institute of Electrical Engineers (AIEE)*, 33 West 39th Street, New York City.

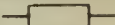
Older symbols were generally quite complicated usually showing both the physical outline and the mechanical details of a device. Because of the wide difference in appearance and construction of similar devices offered by different electrical manufacturers a great deal of confusion and misinterpretation of wiring diagrams are commonly encountered.

Various fundamental symbols commonly found on wiring diagrams and employed by representative electrical manufacturers are given on pages 63 to 72.

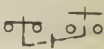
These fundamental symbols portray component parts of elements such as coils, connections, contacts, instruments, transformer, etc. They can be combined in various ways to represent complete electrical devices.

WIRING		
GROUND		
CONDUCTORS (HEAVY LINES MAY BE USED FOR POWER CIRCUITS, LIGHT LINES FOR CONTROL CIRCUITS)	ONE LINE 	COMPLETE 
FUTURE CONDUCTORS		
CROSSING OF CONDUCTORS NOT CONNECTED		
CROSSING OF CONNECTED CONDUCTORS		
JOINING OF CONDUCTORS NOT CROSSING	 	OR  
GROUND CONNECTION GROUND WIRE MAY BE DESCRIBED BY NOTE		
CONDUIT OR GROUPING OF LEADS	 OR  OR  OR  OR 	
CONDUCTOR WITH POLARITY MARK	 OR  OR  OR 	

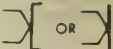
ALARMS		
	ONE LINE	COMPLETE
BELL		
BUZZER		
HORN		
ANNUNCIATOR		
BATTERY		
BATTERY		
STANDARD CELL		
NOTE: THE LONG LINE IS NORMALLY POSITIVE, BUT IN CASE OF UNCERTAINTY POLARITY MAY BE INDICATED THUS.		
CAPACITORS		
FIXED CAPACITOR		
ON COMMUNICATION DIAGRAMS A CAPACITOR IS SYMBOLIZED THUS		
ADJUSTABLE CAPACITOR (FIXED TAPS)	 WITH LEADS	 WITH TERMINALS

RHEOSTATS	
RHEOSTAT	 OR 
MOTOR DRIVEN DIAL TYPE RHEOSTAT (MOTOR OMITTED)	
RESISTORS	
RESISTOR ON COMMUNICATION DIAGRAMS A RESISTOR IS SYMBOLIZED THUS:	 (MAY BE MARKED TO SUIT APPLICATION) 
FIXED RESISTOR	 WITH LEADS  WITH TERMINALS
ADJUSTABLE TAP OR SLIDE WIRE RESISTOR	
ADJUSTABLE RESISTOR (FIXED TAPS)	 WITH LEADS  WITH TERMINALS
SWITCHES	
DISCONNECTING DEVICE (COUPLING OR PLUG TYPE CONTACT)	
DISCONNECTING SWITCH (ONE POLE)	
KNIFE SWITCH (ONE POLE)	
KNIFE SWITCH	 OR 

MISCELLANEOUS SWITCHES

PUSH BUTTONS	 (NORMALLY CLOSED) OR  MAY BE USED ON ELEMENTARY OR SCHEMATIC DIAGRAMS  NORMALLY OPEN) OR 
PUSH BUTTON OPEN AND CLOSED SPRING RETURN)	
PUSH BUTTON OPEN AND CLOSED (NON-SPRING RETURN)	
LIMIT SWITCH CONTACTS	 

FUSE

FUSE		FUSE ELEMENT	
THERMAL ELEMENT			
THERMO-COUPLE		   OR 	

TRANSFORMERS

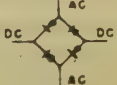
TRANSFORMER		
1 ϕ TWO WINDING TRANSFORMER		
3 ϕ BANK OF 1 ϕ TWO WINDING TRANSFORMERS	 OR 	

INSTRUMENTS & METERS	
INSTRUMENT OR METER	 OR  (SEE NOTE 1)
AMMETER	 OR 
VOLTMETER	 OR 
WATTMETER	 OR 
DIRECT CURRENT WATTHOUR METER	

NOTE 1: LETTER WITHIN CIRCLE OR RECTANGLE INDICATES TYPE OF INSTRUMENT WHEN ONLY ONE TYPE (I OR M) IS USED, OTHERWISE 'I' OR 'M' APPEARS WITHIN CIRCLE WITH ABBREVIATION ALONGSIDE

A AMMETER	M INTEGRATING	RD RECORDING DEMAND METER
AM AMPERE-HOUR METER	OHM OHMMETER	S SYNCHROSCOPE
CMC CONTACT MAKING	OSC OSCILLOGRAPH	TLM TELEMETER
CLOCK	PH PHASE METER	T TEMPERATURE METER
D DEMAND METER	PI POSITION INDICATOR	VRM VAR-HOUR METER
F FREQUENCY METER	PF POWER FACTOR METER	VAR VARMETER
G GALVANOMETER	RF REACTIVE FACTOR	V VOLTMETER
GD GROUND DETECTOR	METER	WH WATTHOUR METER
I INDICATING	REC RECORDING	W WATTMETER

NOTE 2: FOR COMPLETE SYMBOL SHOW VIEW APPROXIMATING REAR VIEW OF ACTUAL INSTRUMENT. INDICATE TERMINALS IN RELATIVE LOCATIONS AND SHOW POTENTIAL TERMINALS WITH SOLID CIRCLE, CURRENT TERMINALS WITH OPEN CIRCLE SCALE RANGE AND MANUFACTURERS TYPE NUMBERS MAY BE MARKED ADJACENT TO SYMBOL IF DESIRED.

RECTIFIERS	
DRY OR ELECTROLYTIC RECTIFIER (FOR SCHEMATIC OR ELEMENTARY DIAGRAM)	 OR  HALF WAVE FULL WAVE
RECTIFIER ON COMPLETE DIAGRAMS RECTIFIERS MAY BE SHOWN WITH TERMINALS AND POLARITY MARKINGS. HEAVY LINE MAY BE USED TO INDICATE NAMEPLATE OR POSITIVE POLARITY END.	

CIRCUIT BREAKERS		
	ONE LINE	COMPLETE
AIR CIRCUIT BREAKER		
POWER CIRCUIT BREAKER		
THREE POLE POWER CIRCUIT BREAKER (SINGLE THROW) (WITH TERMINALS)		OR
THREE POLE POWER CIRCUIT BREAKER (DOUBLE THROW) (WITH TERMINALS)		OR
AUXILIARY SWITCH (WITH TERMINALS)	OPERATING MECHANISM END	
THERMAL TRIP AIR CIRCUIT BREAKER (WITH TERMINALS)		

CONNECTIONS — MECHANICAL

MECHANICAL CONNECTION OR SHIELD	
MECHANICAL INTERLOCK	OR BY NOTE FOR EX- AMPLE CONTACTORS "E" AND "R" ARE ME- CHANICALLY INTER- LOCKED
DIRECT CONNECTED UNITS	

INDICATING LIGHTS

INDICATING LAMP



NOTE: LETTER IN SYMBOL INDICATES COLOR—

B BLUE O ORANGE R RED
 C CLEAR O P OPALESCENT W WHITE
 G GREEN P PURPLE Y YELLOW



WITH LEADS



WITH TERMINALS

COILS

(INCLUDING INDUCTORS, REACTORS, FIELD, ETC.)

NON-MAGNETIC CORE

FIXED



ADJUSTABLE TAP OR SLIDE WIRE



ADJUSTABLE BY FIXED TAPS



WITH LEADS



WITH TERMINALS

MAGNETIC CORE

FIXED



ON COMMUNICATION DIAGRAMS A MAGNETIC-CORE INDUCTOR, ETC., IS SYMBOLIZED THUS:



OR



ADJUSTABLE TAP OR SLIDE WIRE



ADJUSTABLE BY FIXED TAPS



WITH LEADS



WITH TERMINALS

OPERATING COIL



OR



BLOWOUT COIL



WITH LEADS



WITH TERMINALS

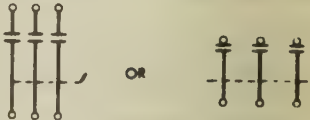
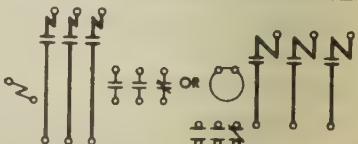
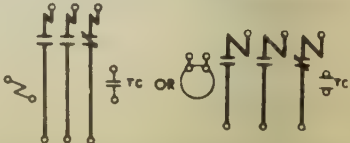
NOTE: COMMUTATING, SERIES, AND SHUNT FIELDS MAY BE INDICATED BY ONE, TWO, AND THREE ZIGZAGS RESPECTIVELY. SERIES AND SHUNT COILS MAY BE INDICATED BY HEAVY AND LIGHT LINES OR ONE AND TWO ZIGZAGS RESPECTIVELY.

CONTACTS — ELECTRICAL

NORMALLY CLOSED CONTACT (NC) (NORMALLY CLOSED DESIGNATES THE POSITION OF THE CONTACTS WHEN THE MAIN DEVICE IS IN THE DE-ENERGIZED OR NON-OPERATED POSITION)	 ON COMMUNICATION DIAGRAM A NORMALLY CLOSED CONTACT IS SYMBOLIZED THUS: 
NORMALLY OPEN CONTACT (NO) (NORMALLY OPEN DESIGNATES THE POSITION OF THE CONTACTS WHEN THE MAIN DEVICE IS IN THE DE-ENERGIZED OR NON-OPERATED POSITION)	 ON COMMUNICATION DIAGRAM A NORMALLY OPEN CONTACT IS SYMBOLIZED THUS: 
NO CONTACT WITH TIME CLOSING (TC) FEATURE	 TC
NC CONTACT WITH TIME OPENING (TO) FEATURE	 TO

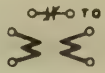
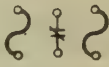
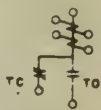
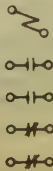
CONTACTORS

FUNDAMENTAL SYMBOLS FOR CONTACTS, COILS, MECHANICAL CONNECTIONS, ETC., ARE THE BASIS OF CONTACTOR SYMBOLS

THREE POLE MANUALLY OPERATED CONTACTOR WITHOUT BLOWOUT COILS	
THREE POLE ELECTRICALLY OPERATED CONTACTOR WITH BLOW-OUT COILS AND 2-NO AND 1-NC AUXILIARY CONTACTS	
THREE POLE ELECTRICALLY OPERATED CONTACTOR WITH BLOW-OUT COILS, 2-NO AND 1-NC MAIN CONTACTS AND 1-NO AUXILIARY CONTACT WITH TIMED CLOSING	

RELAYS

FUNDAMENTAL SYMBOLS FOR CONTACTS, COILS, MECHANICAL CONNECTIONS, ETC. ARE THE BASIS OF RELAY SYMBOLS

OVERCURRENT OR OVERVOLTAGE RELAY WITH 1-NO CONTACT	 OR 
OVERLOAD RELAY HAVING TWO CURRENT COILS AND NC CONTACT WITH TIMED OPENING	
THERMAL OVERLOAD RELAY HAVING 2 SERIES HEATING ELEMENTS AND 1-NC CONTACT	 OR 
RELAY HAVING MAGNETIC TIME DELAY DROP-OUT WITH OPERATING COIL AND BUCKING COIL. 1-NO & 1-NC CONTACT. RELATIVE POSITION OF COILS INDICATED ON DIAGRAM	 BUCKING COIL OPERATING COIL
MAGNETIC TIME DELAY DROP-OUT TYPE RELAY WITH OPERATING COIL, 1-NC AND 2-NO CONTACTS	
FIELD FORCING & ACCELERATING RELAY; NO CONTACT, WITH BLOWOUT COIL; SHUNT & SERIES OPERATING COILS CONNECTED CUMULATIVE	
MULTI-CIRCUIT RELAY WITH 2-NO & 2-NC CONTACTS, OPERATING COIL	 OR 

MACHINES (ROTATING)		
MACHINE OR ROTATING ARMATURE		
SQUIRREL CAGE INDUCTION MOTOR		
WOUND ROTOR INDUCTION MOTOR OR GENERATOR		
3 ϕ SYNCHRONOUS MOTOR OR GENERATOR OR CONDENSER	 	
MOTOR FIELD (SEE NOTE UNDER COILS)	 ONE LINE	
3 ϕ OR 2 ϕ —3 WIRE SQUIRREL CAGE INDUCTION MOTOR OR GENERATOR		
2 ϕ —4 WIRE OR SINGLE PHASE, SPLIT PHASE INDUCTION MOTOR OR GENERATOR OR ROTARY PHASE CONVERTER		
REPULSION MOTOR		
3 ϕ WOUND ROTOR INDUCTION MOTOR, SYNCHRONOUS INDUCTION MOTOR OR INDUCTION GENERATOR		
DC SERIES MOTOR OR 2-WIRE GENERATOR WITH COMMUTATING AND/OR COMPENSATING FIELD WINDING		
DC SHUNT MOTOR OR 2-WIRE GENERATOR		
DC COMPOUND MOTOR OR 2-WIRE GENERATOR OR STABILIZED SHUNT MOTOR WITH COMMUTATING AND/OR COMPENSATING FIELD WINDING		

CHAPTER 3

Control Apparatus

(Construction, Arrangement, Definitions, etc.)

Panel Materials.—Materials most commonly used for control panels are: Asbestos composition (ebony asbestos) and steel.

In the early days of the electrical industry, *marble* was used almost exclusively because of its good dielectric properties and good appearance. Control devices were mounted directly on the panel instead of on individual bases, and all wiring was on the rear of the board.

It was found, however, that control panels of this material were easily marred with scratches and oil stains, and a great deal of effort was required to maintain its attractive appearance.

In order to eliminate this disadvantage, *slate* was used in spite of its inferior and less uniform dielectric properties. Because of its limitation as a dielectric material, the use of slate was at first restricted to the lower voltage installations. Notwithstanding this its use increased to considerable proportions due to its excellent mechanical strength.

One of the detrimental factors in its use was that this material breaks easily and this breakage in handling and transit was serious.

Asbestos composition possesses many advantages as compared to either marble or slate. It is made of a composition material in which asbestos fibre and electrical insulating compounds are mixed and formed under great pressure into smooth surfaced panels.

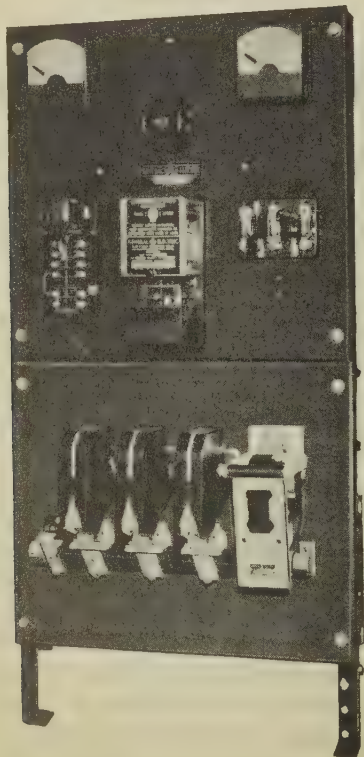


FIG. 1.—Showing typical motor control panel, where the control equipment is mounted on asbestos composition which is supported by an angle iron frame. NOTE.—All wiring is back of board. (Courtesy General Electric Co.)

This panel material has good dielectric properties, a good appearance, is lighter in weight and has a high mechanical strength. In addition, asbestos composition is much easier to cut or drill than either of the two panel materials previously mentioned.

Steel control panels are presently being used by numerous manufacturers since they have the advantage of great strength and durability. Live parts of the equipment to be installed must of necessity be insulated at all points.

Steel panels are usually made of $\frac{1}{8}$ in. stretched leveled steel, the sides being bent into a channel section about three inches deep. The top and bottom edge of the panel are bent into 3 in. angle sections and the corners are welded and ground smooth. All front edges are usually rounded to a $\frac{3}{8}$ in. radius. After being welded and ground, the panels are sand blasted and the first coat of finish applied. When the panel has been completely drilled, it is usually finished in a soft black or any other desired color.

The control devices and instruments are then mounted and the wiring completed.

Wiring on Steel Panels.—Although various manufacturers employ widely different methods of wiring, the usual method in wiring apparatus on steel panels of the previously described type, is to run the vertical wiring inside the side channels where it is concealed by cover plates which may readily be detached. When this method of wiring is being used, only the horizontal run of wires will be visible and this procedure results in a neater job without sacrificing the accessibility of the wiring.

Arrangement of Equipment.—The procedure in laying out of equipment varies with different manufacturers.

The most commonly used procedure is to use a good grade of heavy paper board, the size of the control panel, and on this mark the outline of the equipment to be mounted in full size, together with the exact spacing and diameter of all holes to be drilled for projecting terminals and supporting studs.

After the equipment has been properly located on this paper board, it is carefully transferred to the equipment side or front of the actual panel, and the center of the various holes to be drilled is now transferred to the control panel by means of a center punch.

These paper templates are usually properly titled and carefully cataloged and stored away for use on any similar job when needed.

The location of the equipment as well as the type of panels and enclosure to be used for a particular motor or installation has been very much standardized at the present time.

The definitions, types of control enclosures, etc., used in industrial control applications are given by *The National Electrical Manufacturers Association* (NEMA), and are as follows:

Definitions

Acid-Resistant Apparatus.—Apparatus so constructed that it will not be readily injured by acid fumes.

Drip-Proof Apparatus.—Apparatus so constructed or protected that its successful operation is not interfered with when subjected to falling moisture or dirt.

Drip-Tight Apparatus.—Apparatus so protected as to exclude falling moisture or dirt. Drip-tight apparatus may be semi-enclosed apparatus, if it is provided with suitable pro-

protective integral with the apparatus so enclosed as to exclude effectively falling solid or liquid material.

Dust-Proof Apparatus.—Apparatus so constructed or protected that the accumulation of dirt will not interfere with its successful operation.

Dust-Tight Apparatus.—Apparatus so constructed that dust will not enter the enclosing case.

Fume-Resistant Apparatus.—Apparatus so constructed that it will not be readily injured by the specified fumes.

Gas-Proof Apparatus.—Apparatus so constructed and protected that the specified gas will not interfere with its successful operation.

Moisture-Proof Apparatus.—Apparatus so constructed or treated that it will not be readily injured by a moist atmosphere (such apparatus shall be capable of operating in a very humid atmosphere, such as found in mines, evaporating rooms, etc).

Sleet-Proof Apparatus.—Apparatus so constructed or protected that the accumulation of sleet will not interfere with its successful operation.

Submersible Apparatus.—Apparatus so constructed that it will operate successfully when submerged in water under specified conditions of pressure and time.

Water-Tight Apparatus.—Apparatus so constructed that a stream of water from a hose (not less than 1 in. diameter) under a head of 35 ft. and from a distance of about 10 ft. can be

played on the apparatus for several minutes without leakage.

Weather-Proof Apparatus.—Apparatus so constructed that exposure to the weather will not interfere with its successful operation.

Classification of Standard Types of Non-Ventilated Enclosures

For the majority of control applications, a general purpose control enclosure is adequate. For other applications, however, it may be necessary to protect the control from dust, gases, water, abrasives, etc. Where such conditions exist, *The National Electrical Manufacturers Association* (NEMA) defines standard types of non-ventilated enclosures as follows:

Type I. General Purpose.—A sheet metal case designed to meet *Underwriters' Laboratories, Inc.* general specifications for enclosures as may be in effect from time to time, and primarily to protect against accidental contact. Type I case is suitable for general-purpose application, indoors, and where atmospheric conditions are normal. It serves as protection against dust and light indirect splashing, but is not dust tight. (See fig. 2.)

Type I-A. Semi-Dust-Tight.—A sheet metal case similar to Type I, with the addition of a gasket around the cover. Type I-A case is suitable for general applications indoors and provides additional protection against dust, although it is not dust-tight. This is what has come to be known in the trade as "semi-dust-tight."

Type I-B. Flush Type.—A sheet metal case similar to Type I, designed for mounting in a wall and provided with a cover which also serves as a flush plate.

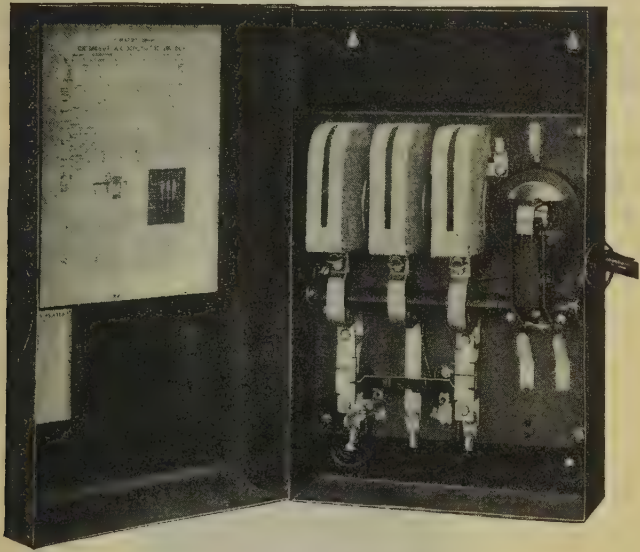


FIG. 2.—Illustrating a three-pole magnetic starter in Type I general purpose case. (Courtesy General Electric Co.)

Type II. Drip-Tight.—A sheet metal case similar to Type I, with the addition of drip shields or their equivalent. Type II case is suitable for application where condensation may be severe, as in cooling rooms and laundries. It meets the requirements of the definitions for drip-proof and drip-tight apparatus. (See fig. 3.)

Type III. Weather-Resistant.—A case of cast construction or of sheet metal of suitable rigidity, with proper protection against weather hazards, as rain and sleet. Type III case is suitable for outdoor application, as on docks, canal locks and construction work, and also for application in subways and tunnels. It meets the requirements of the definitions for splash-proof, weather-proof, sleet-proof and moisture-resistant apparatus. (See fig. 4.)

Type IV. Water-Tight.—A case of cast construction or sheet metal, of suitable rigidity and designed to meet the hose test given under definition for water-tight apparatus. (See fig. 5.) Type IV case is suitable for application outdoors, on ship docks, and in dairies, breweries, etc.

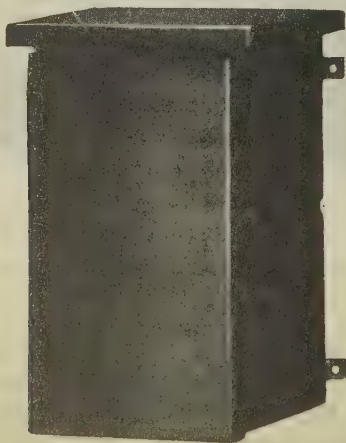


FIG. 3.—Showing external view of a Type II drip-tight enclosure.



FIG. 4.—External view of a Type III weather-resistant enclosure.

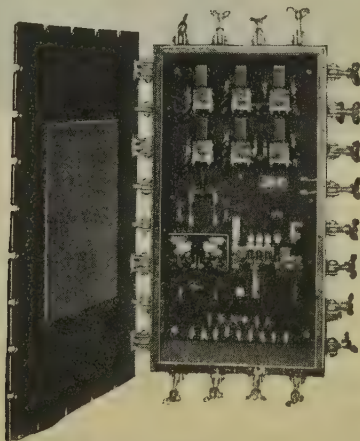


FIG. 5.—Showing a typical motor starter in Type IV water-tight enclosure.

Type V. Dust-Tight.—A case of cast construction, or of sheet metal of suitable rigidity, and provided with gaskets or the equivalent to exclude dust. It meets the requirements of definitions for dust-proof apparatus and of *National Electrical Code* for Classes III and IV locations as may be in effect from time to time. (See fig. 6.) Type V case is suitable for applications in steel mills and other locations where it is desirable to exclude dust.

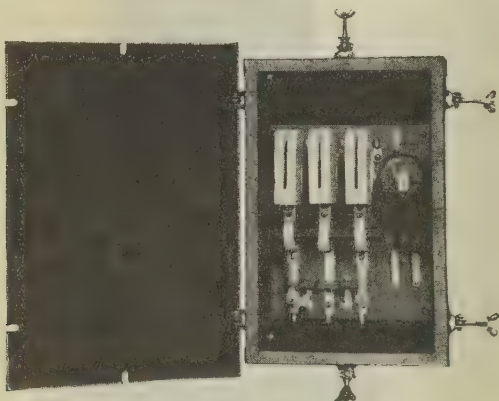


FIG. 6.—Showing a three-pole magnetic starter in Type V dust-tight enclosure.

Type VI. Submersible.—A case designed to meet the requirements as given in definitions for submersible apparatus. Type VI case is suitable for application where it may be subject to submersion in water, as in quarries, mines and manholes. The design will depend on the specified conditions of pressure and time. (See fig. 7.)

Wiping joints for cable connection may be provided as an option.

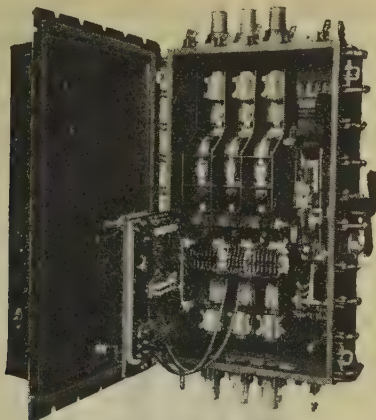


FIG. 7.—Showing motor control equipment in Type VI submersible enclosure.

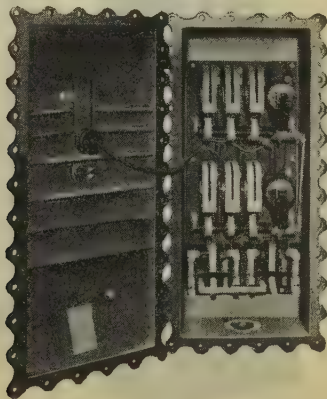


FIG. 8.—Illustrating a three-pole magnetic starter in Type VII hazardous locations, *Class I* air break enclosure.

Type VII. Hazardous Locations—Class I. Air Brake (see Note III).—A case designed for the application requirements of *National Electrical Code* for Class I, Group D, hazardous locations as may be in effect from time to time and designed in accordance with *Underwriters' Laboratories, Inc.* specifications as may be in effect from time to time. (See fig. 8.)

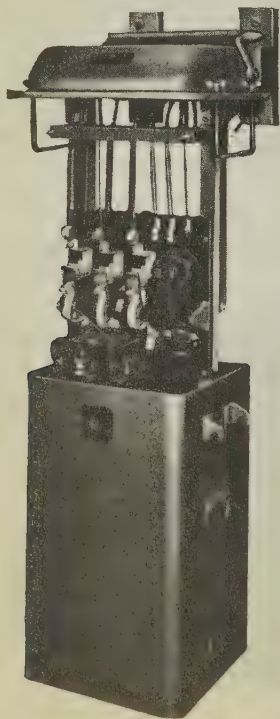


FIG. 9.—Showing typical motor starter in Type VIII hazardous locations, *Class I* oil-immersed enclosure. (Oil tank demounted to show construction details of starter.)

Type VIII. Hazardous Locations—Class I—Oil-Immersed (see Note III).—A case designed for the application requirements of *National Electrical Code* for Class I, Group D, hazardous locations that may be in effect from time to time, and in accordance with *Underwriters' Laboratories, Inc.* specifications as may be in effect from time to time; the apparatus being immersed in oil. (See fig. 9.)

Type IX. Hazardous Locations—Class II.—A case designed for the application requirements of *National Electrical Code* for Class II hazardous locations as may be in effect from time to time and designed in accordance with *Underwriters Laboratories, Inc.* specifications as may be in effect from time to time. (See fig. 10.)

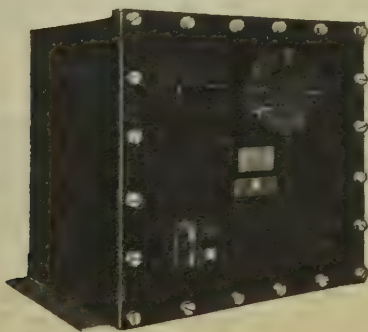


FIG. 10.—Showing external view of a Type IX hazardous locations Class II enclosure.

Type X. Bureau of Mines.—A case designed to meet the requirements of the *U. S. Bureau of Mines*, that may be in effect from time to time. Type X case is for application in coal mines. (See fig. 11.)

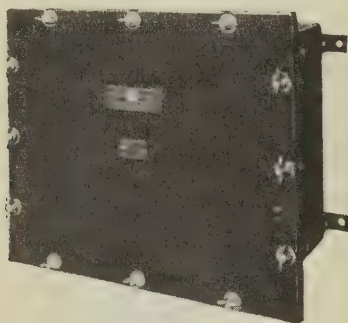


FIG. 11.—External view of Type X Bureau of Mines enclosure.

Note I.—When an enclosure is required to meet the definitions of gas-proof or gas-tight, the selection of a suitable type will depend on whether protection is desired against corrosion, or against explosion or fire.

Note II.—When an enclosure is required to meet the definitions of acid-resistant or fume-resistant, the design will depend on the conditions of exposure.

Note III.—In order to standardize the practice in referring to equipment sometimes known as *explosion-proof* (Types VII and VIII) it is recommended that apparatus designed for use in Class I, Group D locations be described in one of the following manners, whichever is applicable:

1. Control listed by *Underwriters' Laboratories, Inc.*, for use in Class I, Group D locations.

2. Control designed to conform with the manufacturer's interpretation of *Underwriters' Laboratories, Inc.* Standards but not listed nor tested by *Underwriters' Laboratories, Inc.*
3. Control of size and nature for which there are no existing *Underwriters' Laboratories, Inc.* standards nor testing facilities.

Control for Hazardous Locations

The *National Electrical Code* divides hazardous locations into various classifications, described in part as follows:

Class I Classification.—*Class I* locations are those in which inflammable volatile liquids, highly inflammable gases, mixtures, or other highly inflammable substances are manufactured, used, handled, or stored in other than their original containers.

Class I may include such locations as some parts of dry-cleaning and dry-dyeing plants, pyroxylin-plastic plants, spray-painting establishments, inflammable-gas plants, varnish-manufacturing plants, distilleries, rectifying and blending plants producing whiskey and other alcoholic beverage liquors, plants producing industrial alcohol, and establishments or industries involving similar hazardous processes or conditions.

Class II Classification.—*Class II* locations are those in which (1) combustible dust is thrown or is likely to be thrown into suspension in the air in sufficient quantities to produce explosive mixtures, or (2) those where it is impracticable to prevent such combustible dust from collecting in such quantities on or in motors, starters, lamps, or other electric devices that they are likely to become overheated because normal radiation is prevented.

Class II may include such locations as some parts of flour mills, feed mills, grain elevators, starch plants, sugar, cocoa and coal-pulverizing plants and establishments or industries involving similar hazardous processes or conditions.

Class I, Group D, Equipments.—The *Underwriters' Laboratories* recognize two types of construction for equipments to be used in *Class I, Group D*, hazardous locations, the first being what they term as the "air-break" and the second what they term as the "oil-immersed" type. The theory of the "air-brake" type is based on the fact that hazardous gas will get into the enclosure. Experience and careful laboratory tests have proved that gas-tight conduit systems and enclosures for electric apparatus are impractical. The necessary joints cannot be maintained in a permanently gas-tight condition. Therefore, a slow infiltration of explosive vapors must be expected, and vapors may enter when servicing the equipment.

To keep the probable explosion within the enclosure and prevent it from igniting the surrounding vapor, the enclosure must meet the following requirements:

1. Resist the explosive pressure by (a) strength of walls, and (b) strength of fastenings.
2. Prevent escape of flame through (a) joints, (b) operating-shaft openings and (c) screw, rivet, and conduit openings.

Such enclosures are usually made of heavy cast iron, or fabricated from boiler-plate steel. Wide flanges and long shaft bushings are provided, and in general, the construction is very substantial.

The theory of the "oil-immersed" type is that all electric contacts, bolted and soldered joints, and any other part that might produce a spark, will be located sufficiently below the surface of the oil to prevent any arc or spark from igniting the hazardous atmosphere above the oil level. It is clear that with this type of construction, there will be no explosion within the oil tank and, therefore, the tank does not have to be strong

enough to withstand such an explosion, as in the case of the "air-brake" type.

The selection of a NEMA Type VII (air-brake) or a NEMA Type VIII (oil-immersed) enclosure for low voltage applications depends upon several factors. One is the purchaser's preference. Another is the presence of corrosive gases which frequently exist in combination with the explosive gases. The oil-immersed type affords better protection against corrosion. Because an air-brake type must safely withstand the explosion pressure, it is obvious that there is a definite limit beyond which this type is not practical. Many relays and devices are not suitable for operation in oil and in these cases, it is necessary to obtain the "air-brake" type. Since the life of contact tips operating in air is many times that of those operating in oil, it is always advisable to select the air-brake type of construction where frequent operation is encountered, unless other conditions, such as corrosion, dictate to the contrary.

Class II, Group G, Equipments.—The *Underwriters' Laboratories* specify that *Class II, Group G* enclosures shall be of a design providing substantial construction. They must be built so that dust will not enter. The joints are designed and constructed to give a tight fit at all points. If of the metal-to-metal surface type, when assembled they must have a contact surface at least $\frac{3}{16}$ inch in width. If gaskets are used, they must be mechanically attached to the box or cover, and must provide a contact width of at least $\frac{3}{8}$ inch. Shaft openings must meet certain specifications which are prescribed to keep the dust out.

These enclosures may either be cast iron or fabricated steel. Usually the cast iron enclosures have metal-to-metal joints, and the fabricated employ gaskets.

Most air-brake *Class I, Group D* enclosures will be satisfactory for *Class II* use. However, the oil-immersed *Class I, Group D* enclosures are not suitable, unless they are actually made dust-tight to meet the *Class II* specifications.

Enclosure Design

The NEMA recommended practice for design of enclosures is as follows:

1. All enclosures shall be so designed and assembled that they will withstand handling during shipment and installation.
2. There must be sufficient space within the enclosure to permit uninsulated parts of wire terminals to be separated so as to prevent their coming in contact with each other. Enclosures must be such as to permit proper wire connections to be made with adequate spacing of the terminals and ends of conductors from adjacent points of the enclosures.
3. Exposed, non-arcing current-carrying parts within the enclosure shall have an air space between them and the uninsulated walls of the enclosure, including conduit fittings of at least $\frac{1}{2}$ inch for 600 volts or less. Enclosures of sizes, material, or form not securing adequate rigidity must have greater spacing. A suitable lining of insulating material not less than $\frac{1}{32}$ inch in thickness may be considered acceptable where the spacing referred to above is less than $\frac{1}{2}$ inch.

Exception. -For fractional horse power controllers and other small devices, 300 volts or less, where the enclosure is rigid, an air space of $\frac{1}{4}$ inch is permitted between non-arcing current-carrying parts and the uninsulated part of the enclosure.

4. All enclosures and parts of enclosures such as doors, covers, tanks, etc., shall be provided with means for firmly securing them in place. Among the available means are locks, interlocks, screws and seals.
5. Where the walls of the enclosure are not protected by barriers or by a lining of non-combustible insulating material, the arc-rupturing parts of the controller shall have air spaces, as per table I, between them and the walls of the enclosure unless a test on any specific device demonstrates that a smaller space is safe for that particular device.
6. A flush type enclosure for mounting in a wall shall be provided with adjustments to align the device with the flush plate and to compensate for difference in thickness of the wall finish.

TABLE I

*Clearance between Arc-Rupturing Parts and Enclosure**

H.P. Rating	Distance from Contacts in Direction of Blowout in Inches		Vertical Distance above Contacts without Blowout in Inches				Horizontal Distance from Contacts and Distance below Contacts in Inches	
	D.C. and A.C. 300 V. 600 V.		D.C. 300 V. 600 V.		A.C. 300 V. 600 V.		D.C. and A.C. 300 V. 600 V.	
5	1¾	3	4	Barriers	1¾	3	¾	1½
10	2	4	5	Barriers	2	4	¾	1½
50	3	5	6	Barriers	3	5	1	2
100	4	Barriers	Barriers	Barriers	4	Barriers	2	3
Above 100	Barriers	Barriers	Barriers	Barriers	Barriers	Barriers	Barriers	Barriers

*NOTE.—All distances must be measured from the contact tips or arc horns.

Material

The NEMA adopted standard with respect to materials, thickness, etc., of enclosures are as follows:

1. In the following paragraphs, it is assumed that steel (or gray iron for castings) will be the metal employed. Copper, bronze and brass are sometimes used, in which case the requirements given for steel shall be complied with.
2. *Thickness of Casing.*—Cast metal for enclosures, whether of iron or other metal, shall be at least $\frac{1}{8}$ inch in thickness at every point and of greater thickness at reinforcing ribs and door edges; except that die-cast metal may be not less than $\frac{3}{32}$ inch thick for an area greater than 24 sq. in. or having any dimension greater than 6 in. and may be not less than $\frac{1}{16}$ in. in thickness for an area of 24 sq. in. or less or having no dimension greater than 6 in. Cast metal shall be at least $\frac{1}{4}$ in. in thickness at threaded holes for conduit.
3. *Sheet Metal Thickness.*—The minimum thickness required for sheet metal enclosures varies with the size. For solid enclosures without slot or other opening, and for solid enclosures except for a slot for the operating handles or openings for ventilation or both, the sheet metal shall be not less than given in the following table, except that metal shall be not less than No. 20 U.S.S. gauge in thickness at points where rigid conduit is to be connected.

TABLE II

Minimum Thickness of Sheet Metal Enclosures

Maximum Volume of Enclosure in Cu. Ft.	Maximum Area of Any Surface in Sq. Ft.	Maximum Dimension in Inches	Without Supporting Frame. Minimum Thickness U. S. Sheet Steel Gauge	With Supporting Frame or Equivalent Reinforcing. Minimum Thickness U. S. Sheet Steel Gauge
$\frac{3}{4}$	.....	12	20 (0.037)	24 (0.025)
1	.....	18	18 (0.050)	20 (0.037)
...	360	24	16 (0.062)	18 (0.050)
...	1,200	48	14 (0.078)	16 (0.062)
...	1,500	60	12 (0.109)	16 (0.062)
...	Over 1,500	..	10 (0.141)	16 (0.062)

4. All enclosures composed of wire mesh, perforated screens, or grille work shall be provided with a supporting frame.
5. Ventilating openings in an enclosure, including perforated holes, louvers, and openings protected by means of wire screening, expanded metal, or perforated covers, shall be of such size or shape that no opening will permit passage of a rod having a diameter greater than $\frac{1}{2}$ in. except that when the distance between live parts and the enclosure is greater than 4 in. openings may be larger than those previously mentioned, provided that no opening will permit passage of a rod having a diameter greater than $\frac{3}{4}$ in. The wires of a screen shall be not less than No. 16 A.W.G. when the screen openings are $\frac{1}{2}$ sq. in. or less in area, and shall be not less than No. 12 A.W.G. for larger screen openings.

Except as noted in the following paragraph, sheet metal employed for expanded metal mesh, and per-

forated sheet metal shall be not less than No. 18 U.S.S. gauge in thickness when the mesh openings or perforations are $\frac{1}{2}$ sq. in. or less in area, and shall be not less than No. 13 U.S.S. gauge in thickness for larger openings.

In a small device where the indentation of a guard or enclosure will not affect the clearance between uninsulated, movable, current-carrying parts and grounded metal, No. 24 U.S.S. gauge expanded metal mesh may be employed, provided that (a) the exposed mesh on any one side of surface of the device so protected has an area of not more than 72 sq. in. and has no dimension greater than 12 in. or that (b) the width of an opening so protected is not greater than 3.5 in.

6. The requirements of enclosures for floor-mounted controllers for voltages not in excess of 600 volts shall be:

I. Where the surrounding enclosure is 6 ft. or more in height and exposed live parts are not less than 6 in. below the upper edge, no covering is required across the top of the enclosure.

Exception.—Where cranes or other movable apparatus or operations of a special character may introduce possible hazards from above, overhead enclosures may be required.

II. Where the surrounding enclosure is within 6 in. of the floor and exposed live parts are not less than 6 in. above the lower edge, no covering will be required for the bottom.

Installation Clearances

The distance between non-arcing, uninsulated live parts of opposite polarity and between non-arcing, uninsulated live parts and parts other than the enclosure which may be grounded when the device is installed, shall be not less than that given in the following table:

TABLE III
Electrical Installation Clearance

Rating in Volts	Distances in Inches*			
	Through		Across Clean Dry Surface	
	Air	Oil	Air	Oil
51- 150	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{4}$	$\frac{1}{4}$
151- 300	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{3}{8}$	$\frac{3}{8}$
301- 600	$\frac{3}{8}$	$\frac{3}{8}$	$\frac{1}{2}$	$\frac{1}{2}$
601-2,500	1	$\frac{3}{4}$	2	1
2,501-7,000	2	$1\frac{1}{2}$	$3\frac{1}{2}$	2

*NOTE.—The clearance distance should be increased for dirty or moist conditions.

The spacings in snap switches, lamp holders and similar wiring devices supplied as part of industrial control equipment need not comply with the requirements of these standards provided such devices are not employed in the motor circuits.

Temperature and Altitude.—Control apparatus conforming with the *NEMA Industrial Control Standards* shall be suitable for carrying its rated load; when and where the temperature of cooling medium does not exceed 40° C., and where the altitude

does not exceed 6,000 feet, and where only an ordinary amount of moisture and no acid nor conducting or abrasive dust is present.

Control apparatus designed for operation in altitudes above 6,000 feet and not exceeding 15,000 feet shall be *derated* as follows:

1. Continuous duty resistors shall be derated to 75% of their normal wattage rating.
2. Intermittent and starting duty resistors shall be applied on a duty cycle selected on the basis of the next higher "time-on" classification.
3. A magnetic contactor shall be used to open the main line circuit when manual or drum controllers are used.
4. Auto-transformers and control circuit transformers shall be derated to 75% of their normal *kva.* rating.

Unusual Service Conditions of Installations.—These usually incorporate a number of factors which must be carefully considered prior to the time a selection is made. Thus, for example, the use of apparatus in cooling mediums having temperatures higher than 40° C., or at an altitude greater than 6,000 feet should be considered as a special application. There are further unusual conditions which, where they exist, should be called to the attention of the *manufacturers of the equipment*. Apparatus for use in such cases may require special construction or protection.

CHAPTER 4

Magnetic Contactors

(Alternating and Direct Current)

General.—A contactor may be defined as a device, operated other than by hand, for repeatedly establishing and interrupting an electric power circuit.

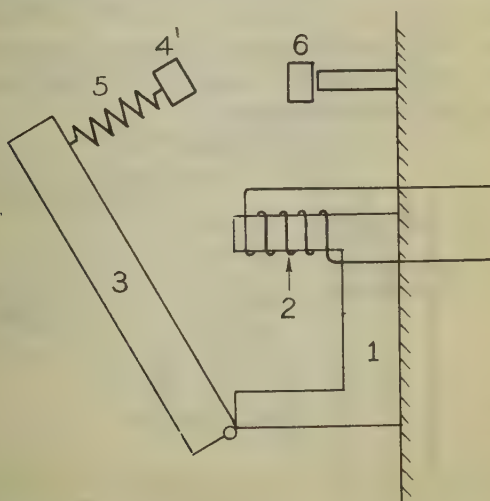


FIG. 1.—Schematic diagram showing the main elements of an A.C. magnetic contactor. The essential elements of the contactor are: 1, stationary magnetic structure; 2, magnetic coil; 3, armature; 4, moving contact; 5, contact spring; 6, stationary contact. It should be noted that the magnetic blowout and the return "tail" spring are here omitted for the sake of simplicity.

Contactors are employed in control as well as in power circuits, single or in groups, with load currents on the main contacts ranging from fractions of an ampere to thousands of amperes, depending upon the particular application.

Although the construction of a contactor is similar to that of a circuit breaker, its action is the exact opposite in that a circuit breaker usually employs an electromagnet for its opening *when a fault occurs*, whereas a contactor employs an electromagnet for the opening or closing of circuit under *normal operating conditions*.

Thus, a contactor is never designed to operate on short circuit currents. This function is delegated to circuit breakers or fuses as the case may be.

Interlocks.—There are two main types of interlocks usually incorporated with magnetic contactors. They are named according to their functioning as:

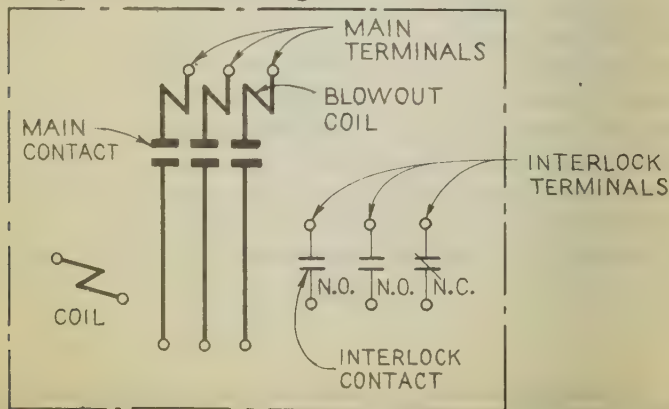


FIG. 2.—Schematic diagram illustrating a three-pole magnetic contactor with two normally open (N.O.) and one normally closed (N.C.) electrical interlocks as usually represented on wiring diagrams. This diagram shows the contactor in its *normal* or *de-energized* position.

1. Electrical interlocks.
2. Mechanical interlocks.

By electrical interlocking is generally meant a system of wiring whereby, when one of the interlocked devices is operating, the control circuit to a second device cannot be completed, or the wiring may be such that the second device or starter cannot be energized until the first device or starter has been put into operation. This is accomplished by auxiliary circuit devices known as *electrical interlocks*, which are open or closed, as the device upon which they are used is operated.

By definition, an electrical interlock is a device which is actuated by the operation of some other device (usually the main contactor) with which it is directly associated to govern succeeding operations of the same or some allied device.

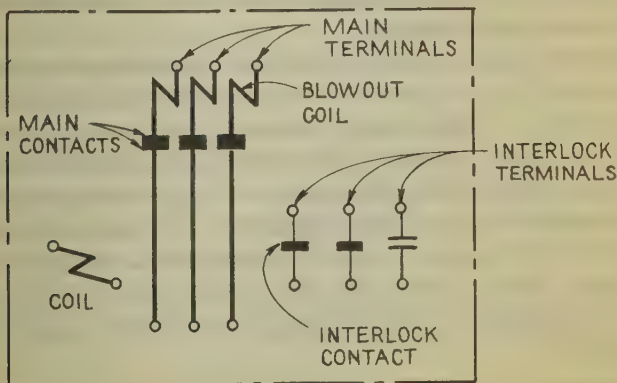


FIG. 3.—Illustrating position taken by the contactor shown in fig. 2, after the coil has been energized and the contactor closed. When the main contacts have been closed, the electrical interlocks take up a position exactly opposite to their normal, or de-energized position. Thus, it will readily be observed that the two normally open interlocks are closed and the previously one normally closed (N.C.) interlock is open. Although a diagram as here represented does not conform with the manufacturer's method of illustrating contactors, it is shown only to illustrate what takes place with respect to the main contactor contacts as well as the contacts of the electrical interlock after the contactor coil has been energized.

Electrical interlocks (sometimes called auxiliary contactors) function as a result of the movement of the main contacts of the contactor to which they are mechanically connected.

Thus, when the main contacts are closed one or several of the electrical interlocks may be in the open position, and one or several in the closed position.

When, on the other hand, the main contacts are opened the interlock contacts which were formerly in the open position, will now be closed and vice versa, see figs. 2 and 3.

Electrical interlocks are usually termed *normally closed** (abbreviated *N.C.*) and *normally open* (abbreviated *N.O.*), depending upon their function in the circuit they operate.

Mechanical Interlocks.—This type of interlocking may be defined as a mechanical arrangement whereby, when one of the interlocked devices is energized, the other is mechanically prevented from functioning.

In certain applications it is necessary to prevent one contactor from closing while a second contactor is closed, and in order to prevent this, a mechanical interlock consisting of a piece of metal (or beam) hinged at the center and arranged in such a way that when both contactors are in the open position, the center piece is in the neutral position. The process of closing one contactor strikes one end of the interlock, moving it toward the panel, thus causing the other end of the interlock to take such a position as to prevent the closing of the second contactor.

A common type of mechanical interlocking is that associated with doors of enclosures housing high voltage control apparatus, whereby the door is prevented from being opened while the contactor or circuit breaker is in the energized position.

*NOTE.—By the term normally open (*N.O.*) and normally closed (*N.C.*) is here meant the position of the contacts of the interlock when the main contacts of the contactor is in the De-energized or Non-operated position.

Electrical and mechanical interlocking are frequently utilized together, one of the best examples of this being an A.C. reversing motor starter.

Shading Coil Effect.—In an A.C. contactor, the magnetic structure must be laminated to reduce core losses, whereas in a D.C. contactor, the magnetic structure is of solid material.

Another difference between A.C. and D.C. contactors is that the former produces a distinct hum or chattering, pitched at twice the frequency of the circuit, whereas the latter is entirely noiseless.

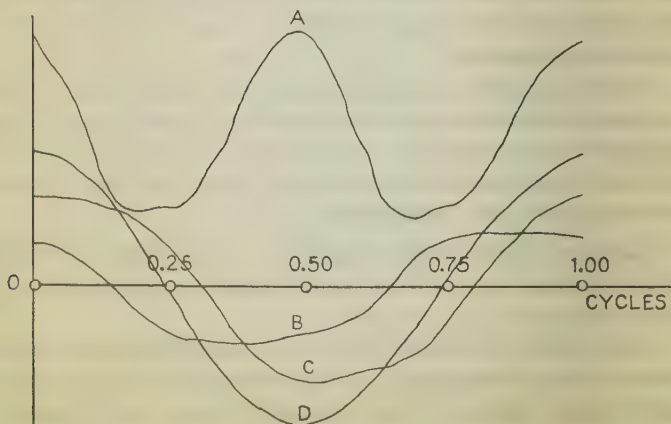
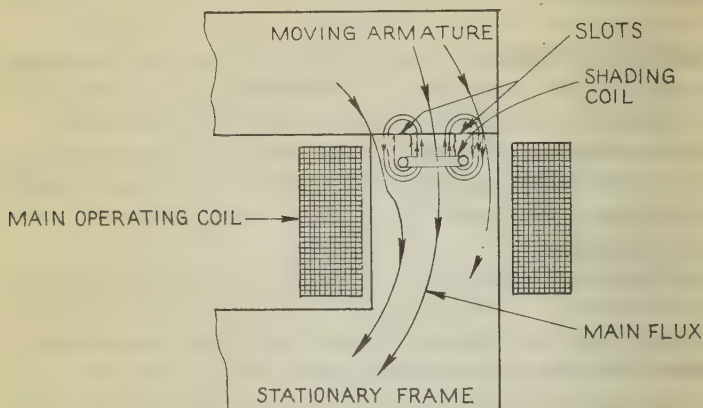
This chattering effect in an A.C. contactor is usually reduced to a minimum by the use of a *pole shader* or *shading coil*. A pole shader may be defined as a short-circuited conductor coil imbedded in one- or two-pole faces of an A.C. magnet. Its function is to divide the pole faces so that only a part of the flux links the short-circuited turn, and the flux from each part of the pole face will exert an independent holding force on the contactor armature.

The resistance and reactance of the shading coil are in such proportion that the induced current in the shading coil is out of phase with the main flux. In this manner the pull on the armature can be maintained without the pulsating effect occasioned by the normal A.C. frequency.

Contactors Coil Power Supply.—At present D.C. magnets operated from copper oxide rectifiers are in common use on the larger sizes of A.C. contactors.

This makes it possible to use a solid magnetic structure rather than a laminated one. Where this method is being used, since the coils are operated from direct current, all troubles incidental to pole shaders as well as the disturbing A.C. hum is eliminated. This method also results in a reduced

power consumption in the magnet coil, and a longer life of the contactor.



Figs. 4 and 5.—Schematic representation of A.C. contactor shading coil and pull-flux characteristics through one cycle of the alternating current. In fig. 5, curve A represents pull on magnet armature; B, flux through unshaded area of pole face; C, flux through shaded area of pole face; D, total flux.

Arc Definition.—Before an attempt be made to describe the problems of arc extinguishing in electrical contactors, it is well to define what is meant by an electric arc.

An electric arc may be defined as a discharge of electricity between electrodes, which has a negative or practically zero volt-ampere characteristics and a voltage drop at the cathode of the minimum ionizing or minimum exciting potential of the material stripped from an electrode at the temperature of the arc. In other words, it is essential that there be a surrounding medium of gas or vapor in order that an arc may be struck by the electrodes.

Magnetic Blow-Out.—The considerable amount of research work done by the various manufacturers of electrical contactors has resulted in great improvements, especially in the field of arc extinguishing, resulting in more effective contactors and a considerable saving in material and space requirements.

Since an arc occurs between the two contactor tips as they open on normal operation, heating and burning of tips occur at that time. Therefore, it is highly desirable, in order to reduce tip burning, to extinguish the arc as quickly as possible, and to keep it from hanging on any one part of the tip surface where the heating would be concentrated.

When controlling relatively small currents, the tip can be opened sufficiently to stretch the arc, so that it is quickly extinguished. Double break tips are also employed for fast extinction of the arc, and give the same length gap with one-half the travel of the movable tip on a single break device. Double break tips have an added advantage in that no flexible shunts are required as on a single break contactor.

When it is desired to employ a contactor for interruption of heavier current, *blowout coils* and *arc chutes* are used to produce a long arc in a relatively small space.

The blowout coil is mounted so that its magnetic field is in the arc path. The coil is connected in series with the contactor itself so that the motor current is flowing through the coil as long as the contactor is closed or as long as there is an arc between the contacts.

The field set up by the blowout coil magnetically repels the arc upward and quickly stretches it within the arc chute to such a length that it is extinguished. The extinction is assisted by the cooling action of the restricted section of the arc chutes.

The blowout coil is used effectively on most contactors carrying a current of 25 *amp.* and more and where it is desirable to interrupt the circuit as rapidly as possible.

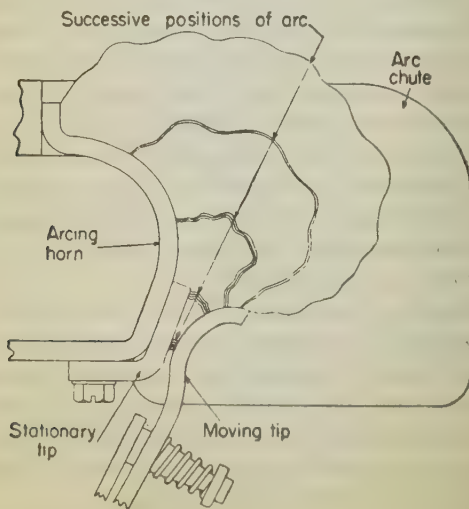
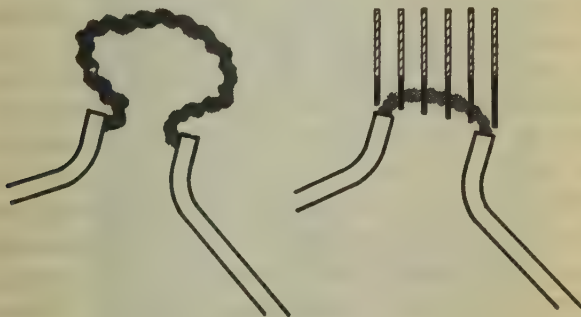


FIG. 6.—Illustrating behavior of arc with a correctly designed blowout.

The Deion* Method of Arc Quenching.—Until quite recently the principal method employed in contactor arc extinction in both A.C. and D.C. circuits has been the use of magnetic blowouts. Here the arc is extinguished by a powerful blowout field and by stretching the arc across arc splitters, thereby lengthening it until instability and extinction occurred.

In A.C. circuits where it is required to interrupt large amounts of current, however, the breaker structure has a tendency to become large and special precautions must be observed to keep the arc within limits of safety.

The *Deion* contactor has been designed by the *Westinghouse Engineers* as a result of the continued demand for a contactor of increased interrupting and current carrying capacity for use in small enclosures.



FIGS. 7 and 8.—Illustrating arcing between contactor tips and arc extinguishing by means of the *Deion* method. Here specially designed *Deion* grids, as shown in fig. 8, not only stretch the arc, but confine and quench it. When the current carrying contacts are opened, the arc rises immediately into the *Deion* grids where it is "sliced" into a series of arcs. At the next zero point on the current cycle, the air adjacent to each grid is de-ionized instantly, the voltage of each grid is insufficient to re-establish the current flow, thus completely quenching the arc.

*NOTE.—The word *Deion* has been coined to designate any type of arc-extinguishing apparatus which functions by rapidly restoring the insulating properties of air or gases in which it operates, by means of other than simply stretching or cooling the arc, utilizing the methods developed in contactor research.

By the use of a properly designed deionizing chamber, the arc may be extinguished in a relatively small space and the gases associated with the arc allowed to escape from the deionizing chamber only after being rendered non-conductive and harmless.

The elimination of the magnetic coil blowout also decreases the heat losses produced in the blowout structure, permitting the current carrying parts to operate cooler, or giving a reduction in the size of enclosure for a given temperature rise. The *Deion* contactor thus makes it possible to have a more compact line starter, more tightly enclosed, with a higher rating, and able to perform more difficult tasks than those built along conventional lines.

Shunt-Type Contactors.—A shunt contactor is a contactor which is operated by a shunt coil energized from a constant potential power source. For direct current operation such contactors are usually of the single and double pole type.

A typical single pole contactor of this type is shown in fig. 9. These are suitable for the remote control of circuits carrying large currents and for the full-voltage control of small motors.

They are used extensively for the control of miscellaneous D.C. circuits such as industrial heating, battery charging, control interlocking, and other similar applications. When used with such accessories as float switches, pressure governors, push button stations, etc., they provide undervoltage protection or release depending upon contact arrangement of accessory used.

The single pole form of contactor consists of a front connected contactor mounted on a compound base which is usually equipped with feet for wall mounting.

The magnet frame consists of a steel casting, and the coil is mounted on a steel core.

Circuit arrangements for a push-button operated single and double pole contactor, respectively, are shown in figs. 10 and 11.

With the coil de-energized the contactor is in its normal or open position. With a pressing of the operating push-button, the coil attracts the movable armature to the stationary core, thus closing the contactor.

As may be observed from fig. 9, the stationary contact is provided with a sizeable arc shield or horn which serves to limit the arc and directs the arc upward and away from the contacts.

The movable contact has a heavy flexible cable, which is connected to an independent stud through the slate, thus avoiding the carrying of the current through the contactor steel frame.



FIG. 9.—Typical D.C. shunt type contactor with arc shield. (Courtesy General Electric Co.)

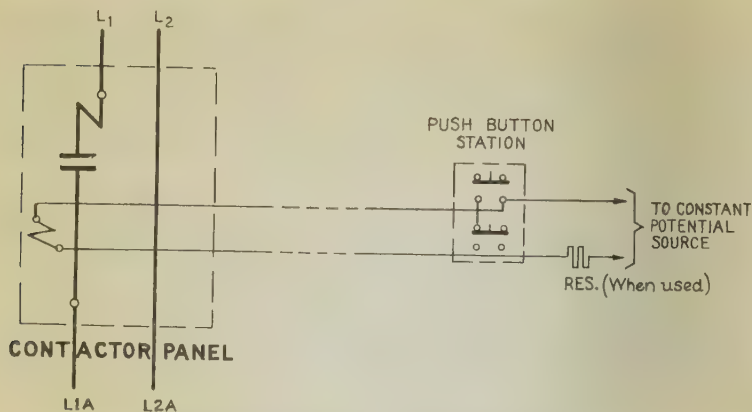


FIG. 10.—Wiring diagram showing wiring arrangement when a single-pole shunt type circuit breaker is controlled from a push-button station.

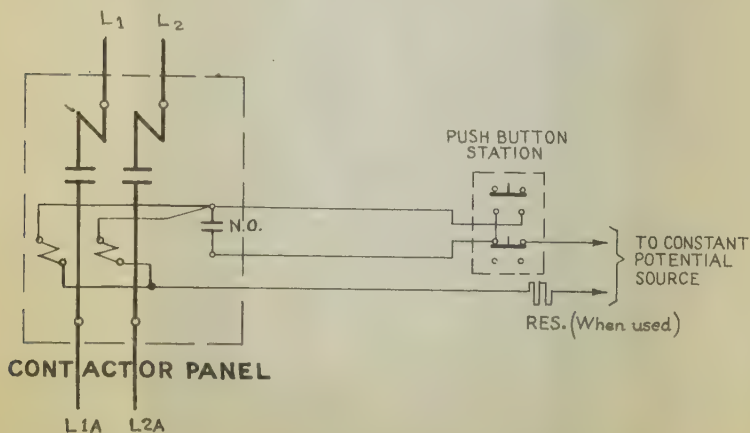


FIG. 11.—Wiring diagram showing methods of control when a double pole shunt type circuit breaker is being controlled from a push-button station.



FIG. 12.—Typical three-pole 300 amp. 600 volts, A.C. contactor with one arc chute removed to show construction. The operating coil is shown on the right and the interlocks on the left of the contactor structure. Contactors of this type are built in standard ratings of from 15 up to 2,400 amp. and for voltages up to 600. (Courtesy General Electric Co.)

Lockout Contactors.—These are used principally as a means of obtaining current limit acceleration on D.C. motors. Such contactors for motor control application are constructed so that the contactor will not close until the current of the circuit has dropped below a definite value. They are made in two general forms:

1. The single coil.
2. The double coil.

The single coil type is usually referred to as a *series contactor*, while the two-coil type is called a *series lockout contactor*. Both of these types, however, possess the lockout feature of the contactor. That is to say they are held open until the current has dropped to some definite value.

The general principle of the operation of the single coil type can be understood from a study of fig. 13. The current passing through the operating coil produces an *m.m.f.* which acts upon two magnetic paths. One path is through the core of the coil, a section of restricted area surrounded by the copper sleeve, the armature, the main air gap, back to the core of the coil. The other path is through the core of the coil, adjustable air gap, tail of armature, armature main air gap back to the core of the coil.

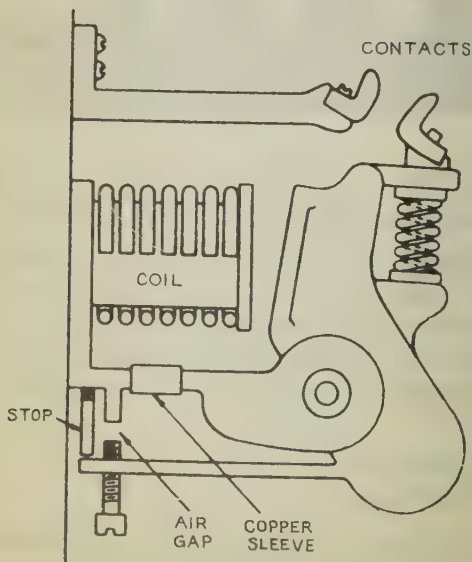


FIG. 13.—Schematic layout showing principal parts of a single-pole, single-coil lock-out contactor.

When no current is passing through the coil, the armature is in the open position. When a large current is passing through the operating coil, the *m.m.f.* is so strong that the path surrounded with the copper sleeve becomes saturated so that the flux through this part cannot exceed a certain amount. The magnetic flux through the adjustable air gap will vary with the current through the operating coil, and this path will not become saturated.

Any flux passing across the adjustable air gap produces an attracting force on the tail of the armature which tends to hold the armature open against the closing force exerted between the core and the main part of the armature.

As the current reduces in value, the flux across the adjustable air gap reduces and thus reduces the holding-out force on the tail of the armature.

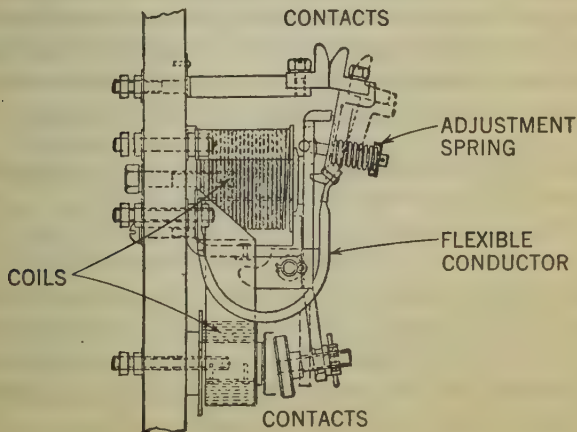


FIG. 14.—Illustrating a two-coil magnetic lock-out contactor.

After the current has reduced to a certain value, which depends upon the adjustment of the adjustable air gap, the holding-out force on the tail of the armature is not sufficient to overcome the closing force exerted by the core upon the main part of the armature, and the contactor closes.

In the two-coil type of series contactor, fig. 14, two coils are connected in series with each other and the circuit to be controlled. The armature is pivoted so that one coil, the larger of the two, acts upon one side of the armature, exerting a force tending to close the contactor. The smaller coil acts upon the other side of the armature and exerts a force tending to hold the contactor open. The areas of the magnetic circuits are so designed that the force tending to close the contactor remains practically constant regardless of the value of current, while the force tending to hold the contactor open varies with the current. Therefore, after the current has decreased to a certain value, the holding-out force is not sufficient to overcome the closing force, and the contactor closes. The air gap of the locking-out circuit can be adjusted so that the current above which the contactor holds open can be adjusted over a wide range.

Inductive-Type Contactors.—These are similar in appearance to the previously described double coil contactor.

They differ with respect to the arrangement of the lockout magnet. In the inductive type magnetic contactor, the lockout magnet is constructed with a heavy iron magnetic circuit.

In operation the relative strength of the main closing and holdout coils are so adjusted that contactor will remain open with full voltage on the main closing coil and approximately 1% of the operating voltage on the holdout coil.

When the magnetic contactor is operated by pressing the start button, both coils are energized simultaneously and the holdout coil is short circuited.

The magnetic circuit comprising the holdout coil is so constructed that a certain time interval is required for the residual flux to decrease to a value, permitting the contactor to close its circuit.

This time interval is adjusted to a suitable value by adjusting the length of an air gap in the holdout magnetic circuit.

Contactor Ratings

Rating Terminology of Contacts.—The rating of a pair of current-carrying contacts is generally expressed in terms of *make*, *brake*, and *carry*.

Make is defined as that value of current transient or steady state, that the contacts can be established without welding.

The current which a set of tips can make is not constant, but depends to a considerable degree on the design of the device on which the tips are used. Some sparking may be visible at *make* because of certain irregularities in the tip surface, and because of the relative motion of the tips as they travel from their first contact point to their final position.

The statement that a device will *brake* a certain current means that it is capable of interrupting the flow of that current without excessive arcing or burning.

The Underwriters' Laboratories specify:

1. That a contactor rated in amperes shall be tested for durability by interrupting its rated current 6,000 times at intervals of 1 second.
2. That it shall interrupt 150% rated current 50 times at intervals of 10 seconds.

It is further specified that D.C. devices shall be tested with a non-inductive resistance load, while A.C. devices shall have an inductive load.

The term *carry* is used to designate the load current that can be conducted without excessive temperature rise. *The Underwriters' Laboratories* specify that *tips* on a motor load shall carry 115% of their ampere rating continuously until the temperatures are constant without exceeding 75° C. rise, and that *tips* on other loads shall carry 100% of their rating and meet these conditions.

The 8-hour rating given devices was agreed upon by the industry in recognition of the fact that most standard devices cannot be energized continuously for days without exceeding a safe temperature rise. It requires the periodic cleaning action of both the physical opening and closing of the contacts, and the arcing, to remove high-resistance oxides which would otherwise form.

The National Electrical Manufacturers Association (NEMA) standard 8-hour open rating in amperes for A.C. contactors shall be 15, 25, 50, 100, 150, 300 and 600 amp.

The open 8-hour rating in amperes for D.C. contactors shall be 25, 50, 100, 150, 300 and 600 amp.

The 8-hour open rating in amperes for A.C. and D.C. contactors rated more than 600 *amp.* has been suggested as 1,200 and 2,400 *amp.*

The intermittent duty ampere rating for A.C. and D.C. contactors for steel mill auxiliary duty and for crane and hoist duty shall be given as shown in Tables I to VIII, inclusive.

Line, reversing and final accelerating contactors used for general purpose and machine tool D.C. magnetic starters shall be given nominal horse power rating, as shown in Table I.

TABLE I

Open 8-Hour Ampere Rating	Horse Power Rating		
	115 Volts	230 Volts	550 Volts
25	3	5	..
50	5	10	20
100	10	25	50
150	20	40	75
300	40	75	150
600	75	150	300

Intermediate accelerating contactors shall be selected so that the open 8-hour ampere rating shall be not less than one-quarter the maximum current for that step.

Contactors Ratings for Steel Mill Auxiliaries.—Standard D.C. contactors employed for steel mill auxiliary service shall be rated as follows:

1. For continuous duty, the horse power rating and number of accelerating contactors shall be as shown in Table II.

TABLE II

Open 8-Hour Contactor Ampere Rating	Horse Power Rating (Continuous)	Minimum Number of Accelerating Contactors
100	25	2
150	40	2
300	75	2
600	150	3

2. For mill duty the horse power rating and number of accelerating contactors shall be as shown in Table III.

TABLE III

Open 8-Hour Contactor Ampere Rating	Contactor Mill Rating	Horse Power Mill Rating	Minimum Number of Accelerating Contactors
100.....	133	35	2
150.....	200	53	2
300.....	400	110	2
600.....	800	225	2* or 3*

*As specified by the user.

The minimum contactor rating to be offered as standard with control for D.C. steel mill auxiliaries shall be the 100-amp 8-hour rating.

Contactor Capacity and Rating—D.C. Cranes.—Standard contactors employed for D.C. crane service shall be as shown in Table IV.

TABLE IV

Open 8-Hour Rating Amperes	Crane Rating		Minimum Number of Accelerating Contactors
	Amperes	Horse Power at 230 Volts	
100.....	133	35	3
150.....	200	55	3
300.....	400	110	3
600.....	800	225	4

NO. E.—General purpose control will be considered as suitable for steel mill accessory machines.

Note 1.—The minimum contactor rating to be offered as standard with crane control shall be the 100 *amp.*, 8-hour rating.

Note 2.—Accelerating contactors shall be the same rating as the line contactors and shall be equipped with blowouts.

Note 3.—The number of accelerating contactors is exclusive of the plugging contactor.

Standard contactors employed for D.C. crane protective panels shall be rated as shown in Table V.

TABLE V
For 230 Volt Motors

Open 8-Hour Rating Amperes	Total Horse Power All Motors at 230 Volts	Largest Individual Motor at 230 Volts
100	55	35
150	80	55
300	160	110
600	320	225

Note 1.—For motors of other voltage ratings, the 8-hour rating of the main line contactor shall be not less than 50% of the combined one-half or one-hour rating of the motors, nor less than 75% of the one-half or one-hour rating of the largest individual motor.

Note 2.—In no case shall the main line contactor of the protective panel be of smaller rating than the largest contactor used on any of the controllers protected thereby.

Contactor Capacity and Rating.—A.C. Cranes (Wound Rotor Motors).—Contactors employed for A.C. crane and hoist service shall be rated as shown in Table VI.

TABLE VI

Open 8-Hour Rating Amperes	Crane Rating		
	Amperes	(Contactors in Motor Primary)	
		Horsepower at 220 Volts	Horsepower at 440 and 550 Volts
100	133	40	75
150	200	60	125
300	400	150	300
600	800	300	...

Note 1.—The minimum contactor rating to be offered as standard with A.C. crane control shall be the 100 *amp.*, 8-hour rating.

Note 2.—Accelerating contactors shall be equipped with blowouts, and shall have a crane rating of not less than the full load secondary current of the motor.

Note 3.—When used for motor secondary control, the ampere rating of a three-pole A.C. contactor with its poles connected in delta, shall be 1.5 times its standard crane rating.

Note 4.—The number of accelerating contactors is exclusive of the plugging contactor for reversing controllers and the low torque contactor for hoist controllers and shall be as shown in Table VII.

TABLE VII

Motor Horse Power Rating	Minimum Number of Accelerating Contactors
75 <i>h.p.</i> and less	3
76 to 200 <i>h.p.</i>	4
Above 200 <i>h.p.</i>	5

Contactors employed for A.C. crane protective panels shall be rated as shown in Table VIII.

Table VIII includes motors of 220, 440 and 550 volt motor rating.

TABLE VIII

Open 8-Hour Rating Amperes	Total Horsepower All Motors		Largest Individual	
	220 Volts	440 and 550 Volts	220 Volts	440 and 550 Volts
100.....	65	125	40	75
150.....	110	225	60	125
300.....	225	450	150	300
600.....	450	...	300	...

Note 1.—For motors of other voltage ratings, the 8-hour rating of the main line contactor shall be not less than 50% of the combined one-half or one-hour rating of the motors, nor less than 75% of the one-half or one-hour rating of the largest individual motor.

Note 2.—In no case shall the main line contactor of the protective panel be of smaller rating than the largest primary contactor used on any of the controllers protected thereby.

Ratings of Contactors and Controllers for Polyphase Multi-speed Motors.—Contactors and magnetic controllers when used with polyphase A.C. multi-speed motors shall be given nominal horse power ratings as shown in Table IX.

TABLE IX

Size Number	Open 8-Hour Ampere Rating	Horse Power Rating		
		110 Volts	220 Volts	440-550 Volts
00 .....	....	$\frac{3}{4}$	$\frac{3}{4}$	..
0	15	1	$1\frac{1}{2}$	2
1	25	$1\frac{1}{2}$	3	5
2	50	5	10	20
3	100	10	20	40
4	150	15	30	60
5	300	..	75	150

Note 1.—For constant *h.p.* (2, 3 and 4 speeds).

Note 2.—For constant and variable torque motors (2, 3 and 4 speeds) the horse power ratings shall be the ratings standard for across the line starters shown in Table XII.

Horse Power Rating of A.C. Low Voltage Contactors for Use with Synchronous Motors, Starters and Controllers.—Standard ratings for full voltage and reduced voltage starting of synchronous motors shall be as shown in Table X.

TABLE X

8-Hour Contactor Ampere Rating	Maximum Horse Power			
	220 Volts		440-550 Volts	
	1.0 P.F.	0.8 P.F.	1.0 P.F.	0.8 P.F.
50	20	15	30	25
100	40	30	60	50
150	60	50	125	100
300	125	100	250	200
600	250	200	500	400
1,200	500	400	1,000	800

Note 1.—The accelerating contactor of single-step primary resistor, auto-transformer, and reactor starters shall have the same rating as the line contactor when the line contactor has an 8-hour rating of 150 *amp.* or less. When the line contactor has an 8-hour rating of 300 *amp.* or larger an accelerating contactor having the next lower rating may be used.

Note 2.—The accelerating contactors of multiple-step starters shall have the same rating as for multiple-step A.C. starters.

Ratings of A.C. Reduced Voltage General Purpose Magnetic Starters.—Reduced voltage starters as covered by this standard include primary resistor starters, auto-transformer starters and reactor starters for squirrel-cage motors, and the primary contactors of secondary resistor starters for wound-rotor motors.

For reduced voltage A.C. general purpose, magnetic starters, reversing or non-reversing, for squirrel-cage or wound rotor motors, with or without overload, disconnecting means or other auxiliary devices, and enclosed in any type of enclosure, standardized groupings of horse powers shall be as shown in Table XI.

TABLE XI

Size Numbers	Open 8-Hour Rating of Controller Amperes	Horsepower Ratings					
		110 Volts		220 Volts		440-550 Volts	
		Three- Phase	Single- Phase	Three- Phase	Single- Phase	Three- Phase	Single- Phase
1	25	3	1½	5	3	7½	5
2	50	7½	3	15	7½	25	10
3	100	15	7½	30	15	50	25
4	150	25	...	50	....	100	..
5	300	....	...	100	....	200	..
6	600	....	...	200	....	400	..

Note 1.—The single-phase ratings in Table XI apply to either two- or three-pole contactors.

Note 2.—The standard horse power ratings adopted for three-phase starters shall apply to two-phase four-wire and two-phase three-wire starters. A current rating of 90% of the 8-hour rating of the contactor employed shall apply, based on the average of the currents in the three legs of the two-phase circuit.

Note 3.—The accelerating contactor of single-step, primary resistor, auto transformer and reactor starters, shall have the same rating as the line contactor when the line contactor has an 8-hour rating of 150 *amp.* or less. When the line contactor has an 8-hour rating of 300 *amp.* or larger, an accelerating contactor having the next lower rating may be used. The accelerating contactors of multiple step starters shall have the same rating as for network starters.

Note 4.—The intermediate accelerating contactors of secondary resistor starters shall be selected so that the 8-hour open rating will not be less than one-sixth of the accelerating peak current. The 8-hour open rating of three-pole delta-connected secondary contactors is 150% of the normal start-connected rating.

Rating of A.C. Across-the-Line Magnetically Operated Starters.—(a) The horse power ratings adopted for 3-phase magnetically operated (magnetic switch) starters shall apply to 2-phase, 3-wire starters. A current rating of 90% of the 8-hour rating of the contactor employed shall apply based on the average of the currents in the three legs of the 2-phase circuit. (b) Across-the-line magnetically operated starters (including reversing) and throw-over switches in any enclosure with or without overload relay or other auxiliary devices for use with any type of induction motor whether a squirrel-cage, double squirrel-cage or wound rotor, shall be given nominal horse power ratings as shown in Table XII.

TABLE XII

Size Numbers	Open 8-Hour Rating of Contactor Amperes	Horsepower at 110 Volts		Horsepower at 220 Volts		Horsepower at 440 and 550 Volts	
		Three- Phase	Single- Phase	Three- Phase	Single- Phase	Three- Phase	Single- Phase
00	...	$\frac{3}{4}$	$\frac{1}{2}$	1	$\frac{3}{4}$	1	....
0	15	$1\frac{1}{2}$	1	2	$1\frac{1}{2}$	2	$1\frac{1}{2}$
1	25	3	$1\frac{1}{2}$	5	3	$7\frac{1}{2}$	5
2	50	$7\frac{1}{2}$	3	15	$7\frac{1}{2}$	25	10
3	100	15	$7\frac{1}{2}$	30	15	50	25
4	150	25	...	50	....	100	....
5	300	....	...	100	....	200	....
6	600	....	...	200	....	400	....

Note 1.—This section applies to all starting, reversing and throw-over switches furnished with any type of enclosure either with or without disconnecting means or other accessories. The enclosures may have operating shafts, push-buttons in the case, reset rods passing through the case, slots for test jacks (with covers thereover) or similar openings which are filled by the shaft rod or other member passing through them.

Note 2.—The single-phase ratings in Table XII apply to either two- or three-pole starters. Standard two-pole magnetic starters reversing and non-reversing for single-phase motors will have overload protection in one leg only.

Ratings of A.C. Across-the-Line Manually Operated Starters.

Across-the-line manually operated starters (including reversing) with or without overload relay or other auxiliary devices in any enclosure for use with any type of induction motor whether squirrel-cage, double squirrel-cage, or wound rotor, shall be given nominal horse power ratings as shown in Table XIII.

TABLE XIII

Size Numbers	Open 8-Hour Ampere Rating	110 Volts		220 Volts		440-550 Volts	
		Three- Phase	Single- Phase	Three- Phase	Single- Phase	Three- Phase	Single- Phase
00	...	$\frac{3}{4}$	$\frac{3}{4}$	$\frac{3}{4}$	$\frac{3}{4}$	.....	...
0	15	$1\frac{1}{2}$	1	2	$1\frac{1}{2}$	2	$1\frac{1}{2}$
1	20	3	$1\frac{1}{2}$	5	3	$7\frac{1}{2}$	5
2	50	$7\frac{1}{2}$	...	15	...	25	...
3	100	15	...	30	...	50	...
4	150	25	...	50	...	100	...

Maintenance and Adjustments

General.—Proper maintenance of contactors play a very important role in their satisfactory functioning and will increase the life-span and economy of their operation.

One important factor to remember is that the use of lubricants on the contacts or bearings should be avoided. Oil quickly collects dust and unless parts are frequently cleaned, will interfere with the operation of the contactor.

Oily surfaces that collect dust may also result in an arc between live parts of the contactor.

Most contactors are furnished with flexible braided copper shunts which are designed to give complete freedom to the moving armature with sufficient current carrying capacity. Burned or badly corroded shunts should be promptly replaced.

Range of Operating Voltage.—Contactors generally are designed to operate properly if the line voltage is within 85 to 110% of the panel name plate rating for A.C. circuits and within 80 to 110% for D.C. circuits. Wider ranges usually require special devices.

Where there is a continuous 10% increase in voltage, suitable coils should be ordered, because with this increase in voltage, there is approximately 50% increase in wattage, which greatly increases the heating of the coil, the deterioration of the insulation is more rapid and the ultimate life of the coil is shortened. There is also an approximate increase of 20% in the pounding effect, resulting in a more rapid deformation of the armature, crystallization of the magnet parts, breaking of the contact tips and increasing noise.

Contact Tip Movements.—The armatures should seal when the proper voltage is applied to the coils, and should open by gravity when the power is cut off. All contact tips should, when closed, make line contacts near the bottom of the face. On opening the final break should be at the top. The rolling and wiping motions when closing and opening keep the contacts in good condition.

Interlock Adjustments.—Electrical interlocks are usually factory adjusted to make contact at approximately the same time that the main contactor tips touch, or even a trifle later. However, for some special applications, the interlocks may make contact before the main tips touch.

To change this adjustment the usual procedure is to loosen the nuts on the front and back of the base and screw the stud in and out to suit the conditions.

Mechanical interlocks are usually so adjusted that with one contactor in the sealed closed position, there is a very small play on the other contactor. This play must not be sufficient to permit the moving contacts of the second contactor to touch the corresponding stationary tips when the tips of the first contactor are just touching.

Importance of Contact Pressure.—Contactors for various classes of service are designed with a definite contact spring pressure. To avoid undue heating of the contacts it is important that spring pressure be maintained at a constant rate.

The contact pressure can be checked to insure they are as required by the manufacturer, by the use of a properly calibrated spring balance as follows:

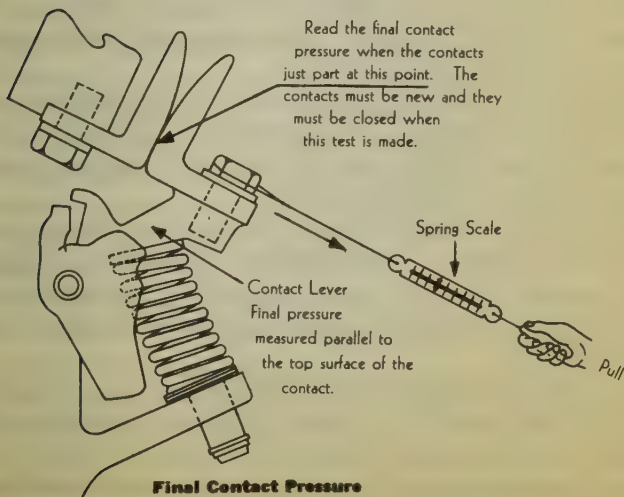
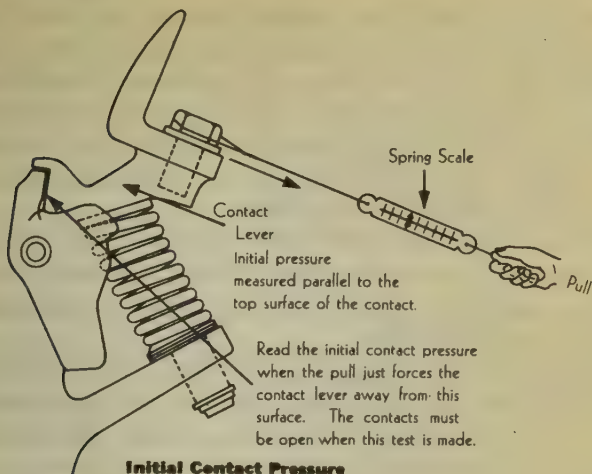
Insert a piece of tissue paper between the mechanically, tightly-closed contacts. Fasten one end of the spring balance to the mounting screw of the moving contact tip and read in pounds the pull required to loosen the paper between the contact tips. In case the contact pressure is below the minimum value required, a new spring should be installed.

Low spring pressure should be guarded against to avoid excessive heating of the contacts. Excessive heating increases the resistance which may cause sufficient arcing to weld the contacts together.

Other Factors Causing Contact Heating.—A contactor has several bolted or spring-closed contacts. Excessively high resistance at these contacts can be the cause of very high temperatures (100 to 200° C.) when the contactor is carrying less than rated current.

The most likely point of high resistance is at the contacts where the movable tips meet the stationary tips.

High resistance, however, may occur at any of the several bolted joints of the contactor. Therefore, if one of these devices begins to develop an excessive temperature, a millivoltmeter should be employed to ascertain which of the several joints has a high voltage drop across it.



Figs. 15 and 16.—Showing method of testing contactors for initial and final contact-pressure.

When the high resistance copper contacts have been located, correction can be made by opening the contact and removing the oxide film with a file (not with sandpaper or caborundum paper). It is unusual to find a high resistance in a bolted joint unless the contactor has previously reached excessive temperatures. When excessive resistances are found in joints, however, the cause should be removed.

Since high resistances will most commonly be found in the active contact, it is a very simple matter to inspect these tips weekly or monthly. If the temperature is unduly high, the tips should be lightly filed.

The foregoing remarks apply particularly to copper contacts, because they oxidize readily and because the copper oxide thus formed has a very high resistance. A file will remove the oxide and again reduce the resistance to a low value.

Electrical interlocks may fail to make circuit because of the oxidation of copper contacts. Sometimes such failure occurs due to the dirt between the contacts.

By using one hemispherical and one flat tip made of silver, both of these troubles will be overcome. The point of the hemispherical will make contact without trapping foreign particles between it and the flat tip.

Excessive wear on contact tips of a contactor indicates that it is operated frequently. For conditions of this kind, where the current exceeds 25 *amp.*, silver should not be used for the contacts, because it does not stand up as well as copper under severe service.

If the service is usually heavy, and if the *r.m.s.* (root-mean-square) of the current is no more than equivalent to three-fourths of the contactor's rating, the tip can be faced with an alloy such as copper-tungsten that will last several times longer than copper.

Rough Contact Tips.—Numerous maintenance men have the erroneous impression that contact tips which have been roughened by service, should be kept smooth. A roughened tip will carry current just as well as a smooth tip. Of course a large projection on a tip caused by unusual arcing, should be removed. A tip that has been roughened by ordinary arcing need not be serviced. If a copper tip becomes overheated, this condition indicates that oxide has developed and should be removed.

Contactor Coil Troubles.—A large percentage of contactor coil troubles are caused by heating. Therefore, if the temperature can be reduced, coil troubles can be greatly reduced.

Since the heating of a D.C. coil will vary as the square of the voltage, and the heating of an A.C. coil will vary about as the cube of the voltage, it follows that coils should be wound for the voltage that exists on the line. If the ambient temperature be high, this precaution is all the more important.

When an A.C. magnet such as a solenoid, is supplied with constant voltage excitation, it requires a large inrush of current to close the armature. When the armature closes, the coil current drops to a normal value. Sometimes it may not close (because of excess friction or some other reason) and in this case the large inrush current may burn out the coil within a few seconds.

Such mishaps can be prevented by the use of a thermal cut-out to protect the coils. When the thermal cutout opens because the armature fails to close, it is merely necessary to replace a small link made of two pieces of metal and held together by a low melting-point solder.

Some of the contributing causes of roasting out of insulation due to overheating of A.C. contactor coils are:

1. Overvoltage.
2. Low frequency.
3. Excessive magnetic gap, caused by faulty assembly of magnet parts, accumulation of dirt, rust, or paint on pole faces.
4. Failure of armature to close completely because of low voltage or mechanical interference.
5. Too frequent operation.

The current on A.C. shunt coils is at minimum value when the armature seals properly with the stationary frame. Any gap in the magnetic circuit lowers the impedance of the coil, which allows the coil to draw more current. If the magnet is accidentally blocked open, or if the voltage is so low that the magnet cannot close, the current is likely to be several times greater than the minimum gap current, and if this condition occurs, the coil may be damaged in a short time.

Unfortunately, the leads on coils are often used as carrying handles. Although the leads are strong enough to support the weight of the coil, this should be discouraged, because it is quite easy to cause a complete or partial fracture of the lead wire or joint, resulting in either an open circuited coil or one that may open-circuit shortly after being installed.

If coils have been wet, it is advisable to bake them as soon as possible in an oven at a temperature of 110°C. to 125°C. This should be done if the coils have been soaked in carbon tetrachloride to remove grease or oil.

If necessary to paint coils, only an approved insulating paint or varnish should be used. Some paints or varnishes contain thinners that will rapidly attack coil and wire insulations. Apply paint while the coils are still warm from baking.

CHAPTER 5

Relays

(Alternating and Direct Current)

Definition.—*By definition, a relay is a device that is operative by a variation in the conditions of one electric circuit to effect the operation of other devices in the same or another electric circuit.*

The function of any relay herein described is to protect the circuit or circuits from dangerous conditions which may arise due to various causes and by disconnecting the motor or apparatus by action of the relay contacts.

Relay Classification.—Relays may be classified according to their types as for example, *plunger, induction*, etc., according to their contacts as *circuit opening, circuit closing*, etc., or according to their function, such as *operating on current, operating on voltage*, etc.

Of the great number of relays used in the various motor protective schemes, the following may be mentioned:

Alternating-Current Relays.

- (a) Operating on current.
- (b) Operating on voltage.
- (c) Operating on change of phase relation.
- (d) Operating on power.
- (e) Operating on frequency.

Direct-Current Relays.

- (f) Operating on current.
- (g) Operating on voltage.
- (h) Operating on power.

Temperature Relays.

- (i) Operating directly on temperature changes, and operating on replica of temperature, such as for example, certain mercury type relays.

In addition to the foregoing protective relays there are:

Auxiliary Relays.

Control Relays.

Signal Relays.

Kinds of Protection.—The various kinds of protection desired depends upon the particular motor application. The most commonly used protection applicable to motors are:

1. Overload protection.
2. Under-voltage protection.
3. Phase reversal protection.
4. Open-phase protection, etc.

Overload Protection is the effect of a device operative on excessive current, but not necessarily on short-circuit, to cause and maintain the interruption of current flow to the device governed.

Under-Voltage or low voltage protection is the effect of a device operative on the reduction or failure of voltage to

cause and maintain the interruption of power in the main circuit.

Phase Under Voltage protection is the effect of a device operative on reduction of voltage in one phase of a polyphase circuit to cause and maintain the interruption of power in the circuit.

Phase Reversal protection is the effect of a device operative on the reversal of the phase sequence in a polyphase circuit, to cause and maintain the interruption of power in the circuit.

Open-Phase Protection is the effect of a device operative on the loss of current in one phase of a polyphase circuit to cause and maintain the interruption of power in the circuit.

Relay Nomenclature.—In most instances relays are termed according to the condition of the circuit or circuits, other than normal, at which they are set to operate. These conditions may be over-current, under-current, over-voltage, under-voltage, etc. The following relay nomenclature will assist in giving some of the specific functions assigned to relays most frequently encountered in motor circuits.

A Current Relay is a relay which functions at a predetermined value of current. It may be an over-current relay, an under-current relay or a combination of both.

A Voltage Relay is one which functions at a predetermined value of voltage. It may be an over-voltage relay, an under-voltage relay or a combination of both.

An Overload Relay is an over-current relay.

A Differential Relay is a relay which functions by reason of the difference between the quantities of the same nature such as current or voltage, etc.

A Frequency Relay is one which functions at a predetermined value of frequency. It may be an over-frequency relay, an under-frequency relay or a combination of both.

An Open-Phase Relay is a relay which functions by reason of the opening of one or more phases of a polyphase circuit, when sufficient current is flowing in the remaining phase or phases.

A Phase-Sequence Relay is a relay which functions in accordance with the order in which the phase voltages successively reach their maximum positive values.

A Step-Back Relay is a relay which operates to limit the current peaks of a motor when the armature or line current increases. A step-back relay may, in addition, operate to remove such limitation when the cause of the high current has been removed.

Notching is a qualifying term indicating that a predetermined number of separate impulses are required to complete operation.

Inverse Time is a qualifying term indicating that there is purposely introduced a delayed action, which delay decreases as the operating force increases.

Definite Time is a qualifying term indicating that there is purposely introduced a delay in action, which delay remains substantially constant regardless of the magnitude of the quantity that causes the action.

Instantaneous is a qualifying term indicating that no delay is purposely introduced in the action of the device.

Automatic* means self-acting, operating by its own mechanism when actuated by some impersonal influence, as for example, a change in current strength; not manual, without personal intervention.

Normally Open and **Normally Closed** are terms used and applied to a magnetically operated switching device, such as a contactor or relay, or to the contacts thereof; signify the position taken when the operating magnet is de-energized. These terms apply only to non-latching types of devices.

Motor Overload Protection

General.—One of the most common elements introduced in a motor circuit is that of protecting the motor against overload.

The overload protection of a motor (or motor over-current protection, as it is referred to in the National Electrical Code) is intended by definition, *To protect the motor, the motor and control apparatus, and the branch circuit conductors against excessive heating due to motor overload.*

It may further be defined as: *The effect of a device operative on excessive current, but not necessarily on short circuit, to cause and maintain the interruption of current flow to the device governed.*

*NOTE.—Remote control that requires personal intervention is not automatic, but manual.

For A.C. motors an operating overload is considered to be a current not in excess of *six times the rated current*; and for D.C. motors not more than *four times the rated current*.

From the foregoing, it is reasonable to assume that excessive currents resulting from torque burdens of the motor output shaft come within the scope of *overload*, whether these conditions are caused by the stalling of the motor, low voltage or single phasing of the supply line.

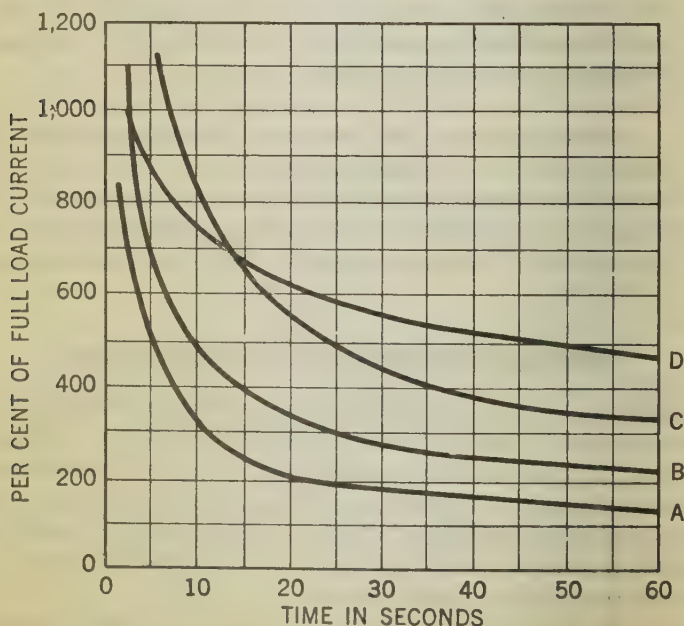


FIG. 1.—Time-current characteristics illustrating the protection of motor and wiring by means of typical thermal overload relay and fuses. In the figure curve A illustrates the time required for the motor to accelerate; B, tripping time of thermal relay; C, time for economical size wire to reach maximum allowable temperature; D, tripping time for fuse of three times motor rating.

The upper limits of excessive heating in a motor is usually set by design standards. Thus, most A.C. motors are rated on the basis of 40° C. ambient* temperature, and the final temperature will be approximately 90° C.

The time required for a motor to reach the final temperature of 90° C. under various amounts of overload is inverse proportional to the square of the current flowing in the motor. From this it follows, that any protective device that is installed with an attempt to match the motor heating characteristics, must be of the inverse-time element type.

Motor Protective Relays

Overload Relays.—The two most common types of motor overload relays are:

1. Those operative directly on temperature.
2. Those operative on the magnetic principle.

To the first class belong the various types of *thermal relays* and to the second the *plunger* and *dashpot type*, the *induction type*, etc.

Thermal Relays.—These forms of temperature relays function as a result of the changing convexity of certain types of metals when heated by an electric current. They are used equally in both A.C. and D.C. circuits. The time of response varies with the amount of overload and design of the relay.

As usually constructed, heat is produced in a resistive type of heater as a result of the motor current flowing through it. Mounted adjacent to the heater is the strip of thermostatic metal anchored at one end, the other end being free to move.

*NOTE.—Ambient temperature is the temperature of the surrounding cooling medium, such as gas or liquid which comes into contact with the heated parts of the motor.

Since the thermostatic metal is made of two metals rolled together, each metal having a different expansion constant, the thermostatic strip will bend or warp when heated. Since one end is solidly anchored, all of the movement occurs on the free end. When the metal is cold, its end position prevents a trigger, on which control circuit contacts are mounted, from tripping. However, as the metal heats, the end moves along the trigger until it comes to a point where the trigger is allowed to trip, and then the control-circuit contacts open.

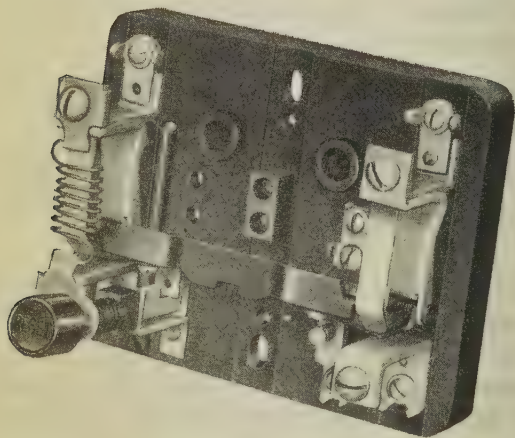


FIG. 2.—Illustrating a two-pole temperature overload relay with detachable heater and thermal unit. Note heater removed from right hand unit to show thermostatic metal strip. (Courtesy General Electric Co.)

A relay of this type is quite accurate, and its operating characteristic is well defined. It is possible to design a heater that will raise the temperature of the thermostatic strip at the same rate as the temperature in the motor with which it is being used, and to adjust the relay so that it will trip the control contacts when the temperature of the motor has reached the allowable maximum. Since some time is required to transmit the heat from the heater coil to the thermostatic strip, it is not affected by momentary current increases. This makes it possible to start the motor with an inrush of six to ten times normal current without tripping the relay.

It should be remembered that since the overload relay operates on current, it cannot be expected to protect a motor under abnormal conditions which do not cause the motor to draw more current. For example, it is possible for the bearings of the motor to become so worn that the rotor rubs against the stator. This may cause the windings to be burned out through mechanical friction, but this may not cause the motor to draw enough extra current to cause the relay to operate.

Heaters for thermal relays are made with different current ratings so that within its limits any starter can be used with different size motors and still afford proper protection by selecting the size of heater that corresponds to the full load current of the motor being used. Tables showing the ampere rating of heaters can be obtained from the manufacturer. In general, the ampere rating of the heater should be approximately 120% of the motor full load current.

Fusible Alloy Relays.—This type of temperature overload relay (sometimes called solder-film relay) is quite commonly used in overload protection of small manual motor starters, and is usually incorporated as part of the motor starting switch.

Principally this relay depends for its function upon the melting of a low-temperature alloy to allow mechanical rotations between two parts normally held rigid by the *frozen* alloy.

Around the solder film is a coil of resistance wire which is connected in one of the motor lines, and as the current passes through this coil of resistance wire, heat is generated, the amount depending upon the amount of current flowing through the heater.

When the temperature of the heater reaches a point where the solder in the solder-film relay melts, a trigger is tripped which mechanically trips the main contacts of the switch.

Molded barriers, which are sufficient protection against arc-overs, and are also mounting supports for switch

Fine-silver contacts of high interrupting capacity. Double-break, umbrella-shaped, movable contacts and flat, stationary contacts

Line terminals

Mounting screws for heater element

Heater element protected by side guards

Molded cover

Molded handle

Load terminals

Thermal unit is solder-film, ratchet type

FIG. 3.—Typical across the line motor starting switch with in-built thermal overload protection feature. A switch of this type is generally used for small induction motors up to about $7\frac{1}{2}$ h.p. (Courtesy General Electric Co.)

After the relay has tripped, the solder hardens, and to reset the tripping mechanism, it is necessary to pull down the operating handle of the switch. It is then possible to flip the operating handle of the switch and start the motor anew. The relay cannot be reset before the solder hardens.

Motor Mounted Thermal Relay.—Another type of thermal overload relay, commonly termed *Thermoguard* relay, responds more accurately to the actual motor temperature than the previously discussed types.

It is mounted directly on or within the motor and is actuated by the heat in the motor itself. This relay uses a small disc, which when heated to a certain predetermined temperature

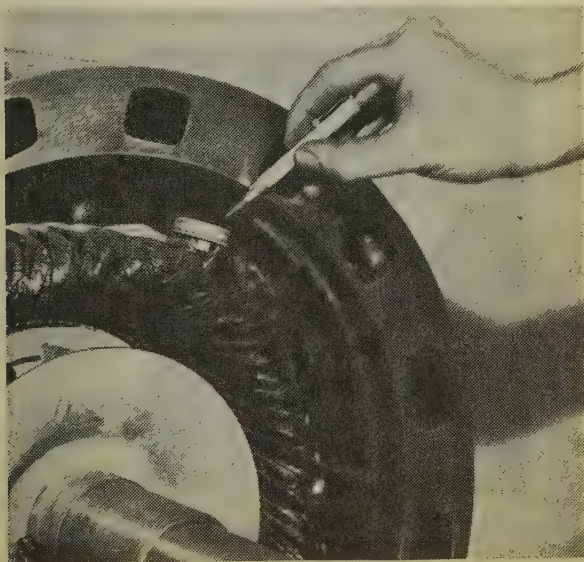


FIG. 4.—Showing Thermoguard relay applied to the motor winding.

snaps quickly from a concave to a convex shape, thereby opening or closing a set of contacts.

The disadvantages with an overload device of this type is that it requires additional control wires between the motor and control and also requires more time to reset after an overload, because of the fact that it cannot cool faster than the motor itself, which has a relatively high thermal capacity.

Magnetic Type Relays.—There are two principal types of magnetic relays used for motor overload protection. They are:

1. The instantaneous.
2. The dashpot type.

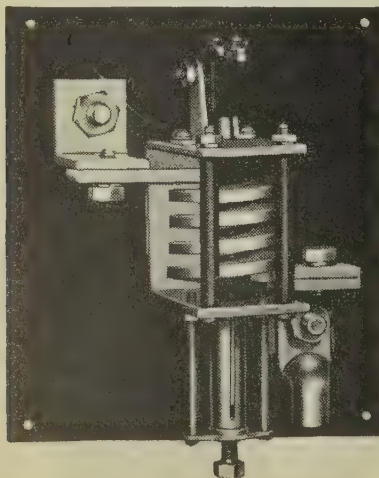


FIG. 5.—Illustrating an instantaneous magnetic type hand reset overload relay.

Instantaneous Overload relays are often used as motor protective devices.

They usually have magnetic operating coils through which the motor current passes. When an overload current flows through the coil, the magnetic pull is sufficient to operate the relay mechanically and cause it to open a control circuit. It is thus independent of time and depends only on the current magnitude for its operation.

The function of a relay of this type is to remove the motor quickly from the line when the over-current exceeds the value at which the relay is set to operate.

It should be remembered, however, that the inrush current to the motor will be determined by the type of controller used, and that an instantaneous overload relay must be set at a current tripping value above the current taken by the motor during its starting operation.

Dashpot Type overload relays in contrast to the previously discussed instantaneous type are designed to operate as a function of time.

In this unit the movement of a solenoid is retarded by means of a dashpot, giving the relay a time-current relationship, or an inverse time characteristic. The solenoid coil is usually connected in series with the motor to be protected.

In a relay arrangement of this type, the mechanical clearance between the piston and the cylinder wall, as well as the viscosity of the enclosed liquid (usually oil) determines its proper functioning. Thus, changes in the viscosity of the dashpot liquid with temperature variations, as well as small amounts of dirt in and around the dashpot, has a tendency to affect its accuracy.

It is mainly because of its inaccuracy that this relay is at present being replaced by relays operating on the thermal principle.

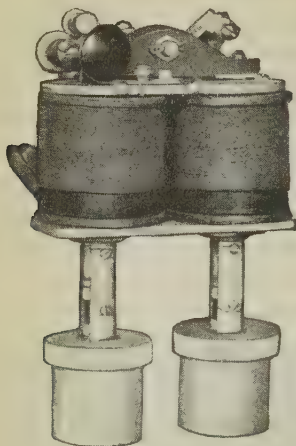


FIG. 6.—Typical dashpot, two element magnetic overload relay with oil dashpots to give inverse-time tripping characteristics. (Courtesy General Electric Co.)

Induction Type Overload Relays.—These relays make use of the induction principle to effect the operation, and for that reason are in many respects similar to the well known induction type wattmeter.

Briefly, the contacts are closed on over-current by the rotation of a copper disc actuated by a “U” shaped driving electromagnet.

The driving torque of the element acts to keep the contacts open against the pull of a pair of spiral springs tending to close them. With a current in excess of that at which the relay is

set to operate, the force exerted by the springs overcomes that exerted by the magnet coil and the disc rotates to actuate the contacts of the relay, which in turn will actuate a trip coil or some other device to open the main motor contactor.

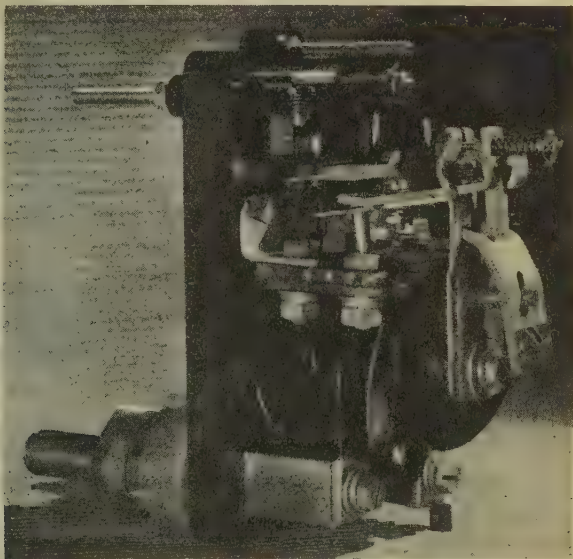


FIG. 7.—Typical induction type T1-2 overload relay. (Courtesy Westinghouse Electric & Mfg. Co.)

In certain relays of this type the winding of the actuating coil is provided with taps for different current settings. When used, these taps are connected to receptacles located in a “tap plate” connected to one of the studs of the relay.

These relays are designed for use on alternating current circuits, and usually operate with a time that is inverse at low over-current values, but approaches a definite time at high over-currents.

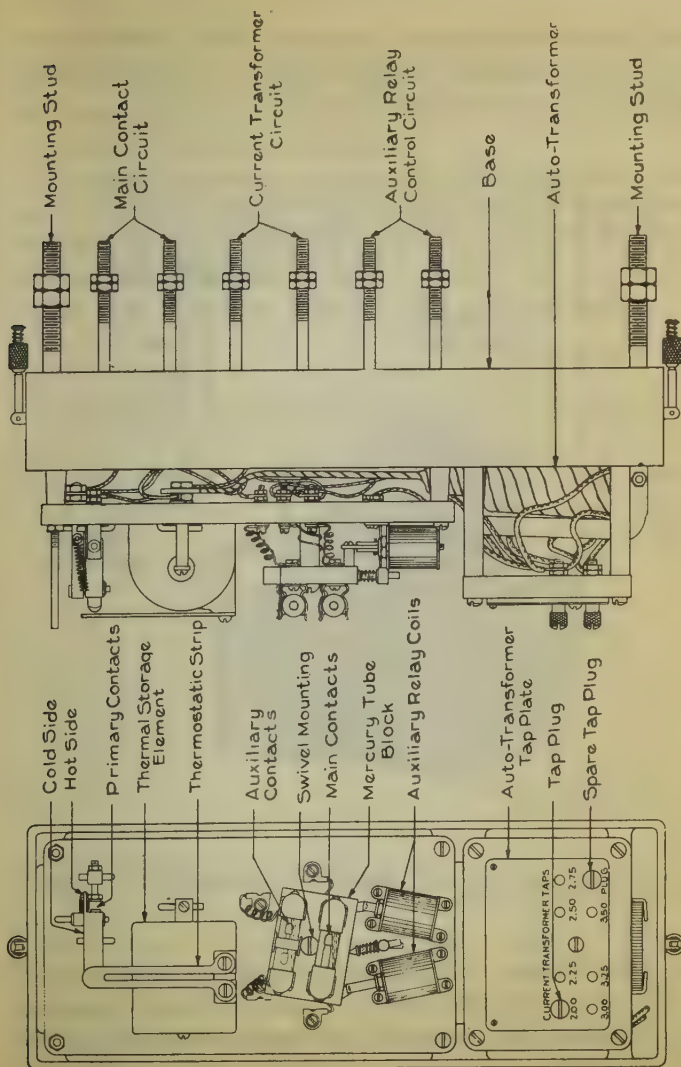
Series Relays.—A representative type of a series overload relay is shown in fig. 5. They are used to protect motors against overload in cases where highly sensitive operation is not essential. It may be set to operate on any desired current by an adjustment of the tension spring which holds the armature open.

Mercury Type Relays.—Another type of overload relay used is the mercury type. Relays of this type usually use one or two tubes partly filled with mercury which due to the action of the current are tilted on its mounting, thus actuating a magnetic coil directly on the motor contactor or through some auxiliary device.

The operation of a typical relay of this type as shown in figs. 8 and 9 is briefly as follows: When the current flows in the machine circuit, a proportionate current flows in the heater and the thermostatic strip of the relay, thereby producing heat which is stored in the thermal storage block.

At low and moderate over-currents the heat is transmitted from the block to the thermostatic metal strip. At high over-currents the thermostatic strip is heated directly by the passing of the current through it. The thermostatic strip is so designed that as its temperature changes, one side of it expands or contracts faster than the other, and the strip becomes more or less curved. This movement of the thermostatic strip closes the hot side of the primary contact on the occurrence of a sustained over-current.

Thus the circuit of one of the auxiliary relay coils is completed, the plunger is pulled down, and the mercury tube block is tilted on its swivel mounting. The mercury in the two tubes flows to the lower end, the main contact opens (or closes) the control circuit which disconnects the machine from the line.



Figs. 8 and 9.—Showing construction principles of a typical mercury type temperature overload relay, used in connection with large machines.

The relay recloses the breaker or contactor after a time which is dependent upon the amount and duration of the over-current. For typical relay connection see fig. 10.

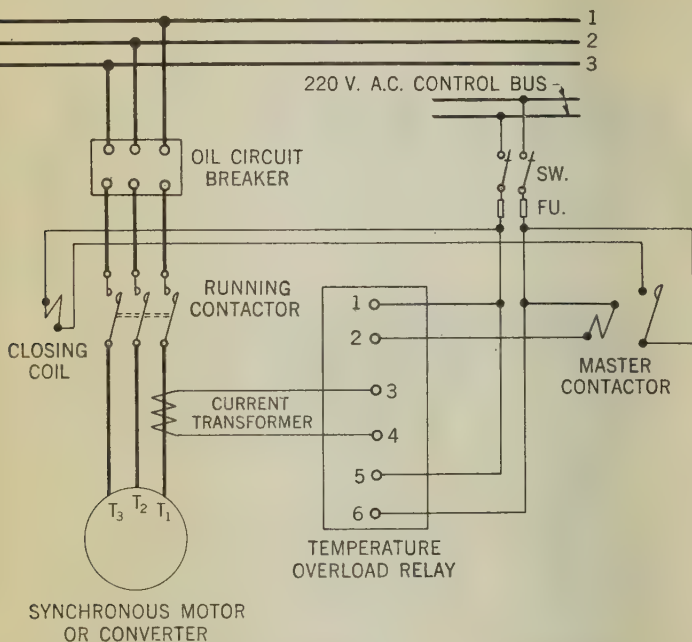


FIG. 10.—Showing typical wiring diagram for protection of synchronous motor or converter against over-temperature due to overload.

Time Delay Relays.—Relays of this type are used for controlling the rate of acceleration of motors or other functions where a predetermined time after the performance of another function is required.

The principle of operation employed in any given type of time delay relay, depends upon the service requirements and may be motor operated, decay of flux in magnetic relay, or may operate on thermal principles, etc.

In the *motor operated type*, the relay usually consists of a small motor driving a set of gears which operate contacts after a definite time interval, which may be adjusted to suit operating conditions. The time setting of a relay of this type can be varied from about one second to several minutes.

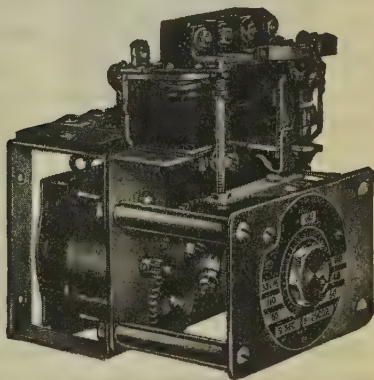


FIG. 11.—Typical motor operated time-delay relay, for A.C. operation. (Courtesy Ward Leonard Co.)

One type of time limit relay based upon the *decay of flux principle*, has two types of coils, one with a standard spool body and another with a copper jacket in the center. The standard coil is used to close the relay on applications of voltage, and in some cases gives a time delay drop-out when the coil is shorted.

The copper jacketed coil is used to give a time delay drop-out when the coil circuit is opened. The decay of the flux in the magnetic circuit when the coil is short-circuited or open-circuited, in the case of the copper jacketed coil, occurs at a given rate and, therefore, keeps the magnet from opening until a definite time interval has elapsed.

Voltage Protective Relays.—In certain motor applications it is necessary to employ relays which are designed to operate on a certain specified voltage.

In these applications a very sensitive relay is required. The operation of a relay of this type is substantially as follows: Under normal voltage conditions, voltage applied to the relay coil either directly or through a suitable transformer holds the plunger up and the contacts open. With a change in voltage the plunger acts to close a pair of contacts, actuating a trip coil or other device to open the motor circuit breaker or contactor.

Single-Phase Reverse-Phase and Reverse-Current Protective Relays.—Relays for these types of motor protection are designed to be in a balanced condition as long as operating conditions are correct. When a single-phase reverse-phase or reverse-current condition exists, the relay coils are subjected to unbalanced forces that operate the relay control contacts. These contacts in turn operate either to stop the motor, or prevent the starting of the motor.

Field Failure Protective Relays.—On direct current and synchronous motors, there is often need for field failure protection.

On D.C. motors a break in the field circuit results in excessive speeds, in some cases sufficient to destroy the motor. A field

failure in a synchronous motor causes it to run as an induction motor. The squirrel-cage or amortisseur winding is generally not designed for the heavy induced current continuously and may be damaged or burn out entirely.

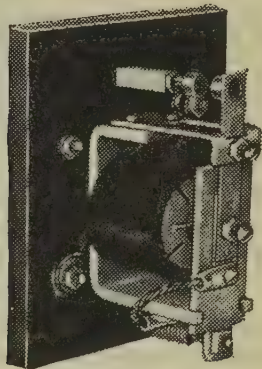


FIG. 12.—Typical field-failure relay for open field protection (D.C. motors). In a relay of this type, the operating coil is connected in series with the shunt field of the motor, and its switch contacts are so connected that when they are opened or closed (as the case may be) it will stop the motor, in case of an open field circuit. (*Courtesy Ward Leonard Co.*)

Field failure relays have their coils connected in series with the motor field circuit, so that when the field circuit is open and no current flows the relay contacts open and operate the control circuit to stop the motor.

In order to design relays that adequately protect motors, a great deal must be known about motor characteristics. Access by control designers to the mass of information accumulated from all kinds of motor tests has permitted them to design a line of motor relays that are thoroughly reliable in operation.

Maintenance and Adjustments

Thermal Overload Relays.—Since the function of a temperature overload relay of this type is to protect the motor under all ambient temperatures, its final temperature should be the same as that of the motor or 90°C . This means that the motor can have a 50°C . temperature rise in a 40°C . ambient.

From this it follows that the relay should just trip if placed at 90°C . ambient, or in a pail of water held at that temperature. If a relay does not function correctly it should be immersed in a pail of water kept at 90°C . and adjusted so that it will. This adjustment should not be made by bending the thermoflex strip. If this method of checking or adjustment does not provide the necessary degree of protection to the motor, it can be assumed that the size of the relay heater is incorrect.

Since the function of this relay is based upon temperature changes, it is necessary that the following precautions be observed:

- (a) It should not be placed in a strong draft, such as that from a window or a circulating fan. If necessary to place it in such a position, it should be shielded by a suitable cover.
- (b) Conversely a temperature overload relay should not be located above steam pipes or other sources of heat.
- (c) Briefly, a relay of this type should be in an ambient temperature that does not differ greatly from that of the motor to which it is connected.

Dashpot Type Relays.—In a relay of this type the movement of a solenoid is retarded by means of a dashpot, giving a time-current relation that is called an inverse time characteristic.

Thus, a dashpot is essentially a close fitting device that is easily affected by dirt, gumming of the oil, and corrosion of the close fitting parts.

Also the torque of the magnet varies with the position of the solenoid armature in its coil. It is largely because of these disadvantages that other types of relays have been developed.

If trouble be experienced due to tripping while starting the motor or shortly after getting up to speed, the following can be done:

- (a) A heavier oil may be used if the relay almost holds.
- (b) A starting contactor can be used that does not include the overload relay in the circuit. After the motor is up to speed, the running contactor can close and the starting contactor can open, connecting the overload relay into the circuit. This is a rather complicated method, but it is sometimes used.
- (c) The final alternate is to replace the dashpot with a temperature type of overload relay.

Time Delay Relays.—This type of relay is used for controlling the rate of acceleration of motors and for numerous other functions where a short time delay action is needed.

In the escapement type, a pendulum is used as the governing means which makes it necessary to mount the relay in a definite position with respect to the motion of the pendulum.

It is not always possible, however, to mount the relay in the proper position, and when it is out of true position, it is less dependable. Shortening the pendulum makes it possible to

tip the relay farther from the vertical, but the shorter pendulum results in a shorter time delay.

To overcome this limitation a new type of relay has been designed with a balanced pendulum. In principle the two devices are the same, but mechanically they are quite different.

If the old type escapements fail to time properly, their mounting position should be checked. If the application be such, however, that it is difficult to mount and keep the relay in the proper position, a later type relay incorporating a balanced pendulum should be considered.

CHAPTER 6

Remote Control and Miscellaneous Equipment

Push-Button Stations.—Push-button stations are used in the majority of magnetic motor controls. They may be mounted either separately at a remote point or in the cover of the motor starter.



Figs. 1 to 5.—Showing various types of push buttons.

Push-button stations are generally of two types:

1. The momentary contact type.
2. The maintained contact type.

Sometimes, however, a combination of both types may be provided.

In a momentary contact push-button, when the button is pressed, a contact is made only as long as the finger depresses the button.

In a maintained contact type, on the other hand, the button when depressed makes and maintains a circuit even when the finger is removed from the button.

Thus, in a motor push-button station of the maintained contact type having a *start* and *stop* button, to open the contacts and stop the motor, the *stop* button, which is adjacent to and mechanically interlocked with the *start* button, is pressed. This forces open the contacts of the *start* button.

Momentary contact buttons are made either *normally closed* or *normally open*, or they may be provided with two sets of stationary contacts, so that one set is opened and the other is closed when the button is pressed.

Individual push-button stations are usually available with from one to seven buttons, or more, so that a series of operations can be controlled from one point.

In addition to the operating buttons, push-button stations can be equipped with self contained indicating lights in various colors. The function of these indicating lights is to show when the motor is running at full or at some intermediate speed, or to indicate various conditions of the operation.

Push-button stations are ordinarily mounted on the wall or on the surface of the controlled machine, or they may be mounted flush with the surface of the machine frame or on a panel board.

For general purpose applications where atmospheric conditions are normal, push button stations are usually housed in sheet metal enclosures. Stations in special enclosures that are dust or watertight are available as well as stations for installations in hazardous atmospheres.

Push-Button Ratings.—Push-button stations are usually made in two classes, depending upon the amount of current the contacts are required to carry, as:

1. Standard duty.
2. Heavy duty.

The following table indicates contact ratings for the two classes of push-button stations when operating in an alternating or a direct current circuit:

TABLE I*

	220 Volts A.C.		230 Volts D.C.	
	Heavy Duty Amperes	Standard Duty Amperes	Heavy Duty Amperes	Standard Duty Amperes
Make.....	25	12	2	1
Brake.....	2	1	$\frac{3}{4}$	$\frac{1}{2}$
Carry.....	15	10	15	10

*NOTE.—Push buttons are usually made with voltage ratings of from 110 to 550 volts. For contact ratings of push buttons to be used on other voltages than those given in Table I, refer to manufacturer.

Marking of Push-Button Nameplates.—The arrangement and markings for push-button nameplates as recommended by the *National Electrical Manufacturers Association* (NEMA) are as follows:

Standard Duty Push-Button Stations

<i>One Button</i>	<i>Two Button</i>	<i>Three Button</i>
Start	Start-Stop	Forward-Reverse-Stop
Stop	Forward-Reverse	Open-Close-Stop
	Open-Close	Up-Down-Stop
	Up-Down	†Raise-Lower-Stop
	†Raise-Lower	

Heavy Duty Push-Button Stations

<i>One Button</i>	<i>Two Button</i>	<i>Three Button</i>
Start	Start-Stop	Start-Jog-Stop
Stop	Run-Stop	Run-Jog-Stop
Jog	Forward-Reverse	Forward-Reverse-Stop
Reset	Fast-Slow	Open-Close-Stop
*Inch	Open-Close	Fast-Slow-Stop
	Up-Down	Up-Down-Stop
	†Raise-Lower	†Raise-Lower-Stop
		Start-*Inch-Stop
		Run-*Inch-Stop

*Jog is preferred.

†Up-Down is preferred.

Marking of Push-Button for Multi-Speed Motor Controllers.—Push-button stations for use with multi-speed motors as recommended by NEMA shall be as follows:

When mounted vertically, the lower button shall be the stop button; next, the lowest speed button followed by those for consecutively higher speeds.

When mounted horizontally, the right hand button shall be the stop button; next, the lowest speed button, followed by those for consecutively higher speeds.

Push Button Circuits

In wiring of push-button circuits there are two terms which are sometimes confusing. They are:

1. Low-voltage protection.
2. Low-voltage release.

Low-voltage protection is defined as: *The effect of a device operative on the reduction or failure of voltage, to cause and maintain the interruption of power to the main circuit.*

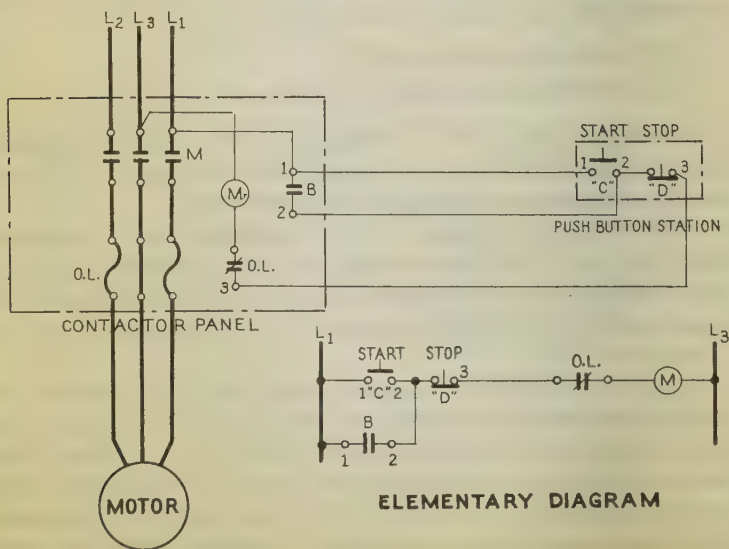
Low-voltage protection allows the control to be removed from the line if the power source fails or a disturbance occurs that causes the line voltage to drop to a very low value. In order to start the apparatus again, it is necessary to actuate the start button.

In order to obtain low-voltage protection, it is necessary to have a start button that closes the control circuit only when it is being held down. An electrical interlock that is closed when the control has functioned parallels the start button and keeps the control circuit closed after the start button is released. When the control drops out because of voltage failure, the interlock opens the control circuit, thus giving protection against unsupervised starts when power returns.

Low-voltage release, on the other hand, allows the control to drop out if for any reason the power source voltage is inadequate, but when the voltage again reaches sufficient value the control will function automatically to connect the apparatus to the line through the proper starting sequence.

Low-voltage release is defined as: The effect of a device operative on reduction or failure of voltage to cause the interruption of power to the main circuit; but not prevent the re-establishment of the main circuit on return of voltage.

These two types of control circuits, commonly known as two- and three-wire control, require different type of push-buttons.

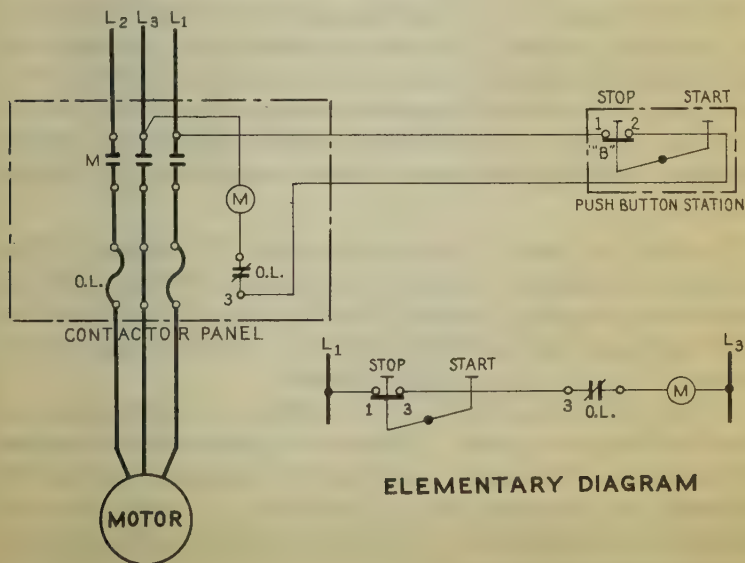


FIGS. 6 and 7.—Wiring diagrams showing method of wiring to obtain low voltage protection.

Low-voltage protection is secured by a momentary contact push-button type, whereas the *low-voltage release* control circuit requires a push button that remains closed until released by hand. This latter type of push-button is known as the *maintained contact type*.

Figs. 6 and 7 show the diagrams for a low-voltage protection push-button connection, and figs. 8 and 9 connection diagrams for a low-voltage release.

With reference to fig. 6, low-voltage protection is provided for in the following manner: Contactor *M* handles the motor circuit. It contains a normally open contactor holding interlock *B*, which closes when the contactor is closed. The two-



FIGS. 8 and 9.—Wiring diagrams showing method of wiring to obtain low voltage release.

button, push-button station consists of a normally open *start* contact *C* and a normally closed *stop* contact *D*. When contact is made momentarily at *C* by pressing the *start* button, the contactor coil *M* is energized and contactor *M* closes, which in turn closes the interlock circuit *B*. It will be noticed that the interlock *B* parallels the start contact *C*. The contactor is, therefore, held in through the interlock circuit *B*, even after the start contact *C* opens up when the finger is removed from the button.

In case of voltage failure, coil *M* is de-energized and contactor *M* opens, which in turn opens interlock circuit *B*. When voltage returns, the contactor will not close until the circuit is again established at *C* by pushing the *start* button.

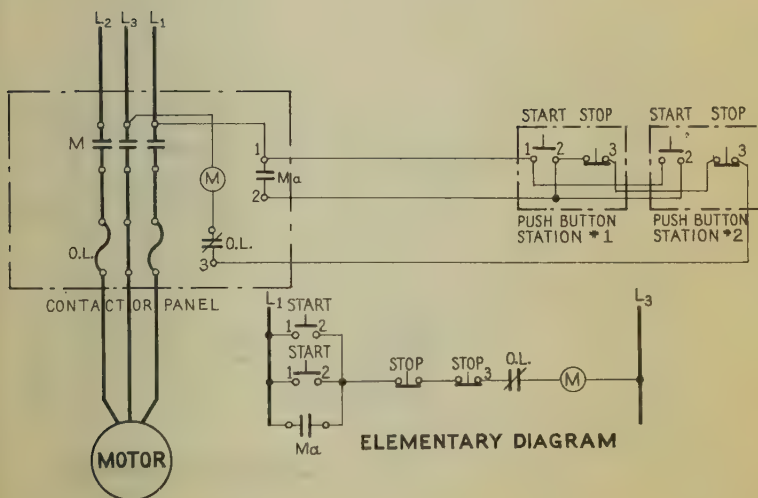
With reference to fig. 8, low-voltage release is provided for in the following manner: The control consists of a contactor *M* for handling the motor circuit, and a maintained contact control switch *B*. Switch *B* can be a knife switch, a float switch, a pressure switch, or a maintained-contact push button station whose contacts close and remain closed regardless of the voltage on them.

To start the motor, the control switch *B* is closed. This energizes the contactor coil *M*, the contactor *M* closes and the motor is connected to the line. Now if voltage fails, the coil *M* is de-energized and contactor *M* opens. Nothing happens to contact *B* as a result of voltage failure.

A control button does one of two things—it either makes a circuit or breaks a circuit. Heavy-duty push-button stations are arranged so that either operation or both operations can be obtained on the same unit. This ability to make or break circuits is exceedingly useful when more than just the start and stop functions are desired.

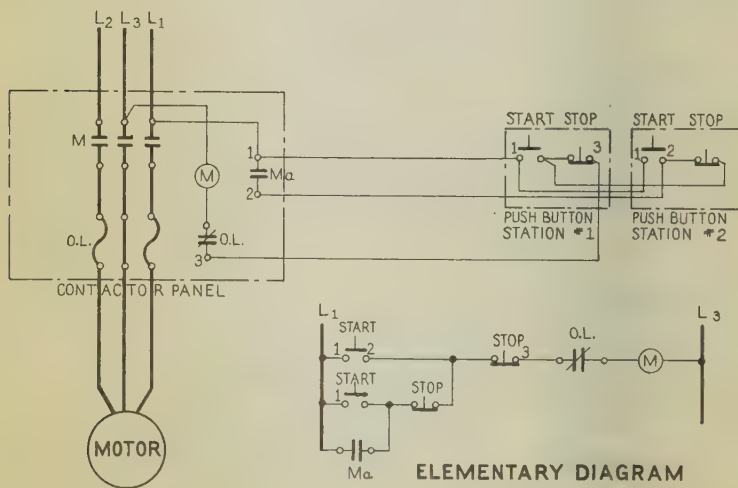
Any combination of control sequence for low-voltage protection can be obtained by applying these two fundamental rules:

1. Wire all stop buttons in series with the holding coil, with each other, and with the electrical interlock.
2. Wire all start buttons in parallel with each other and with the interlock.



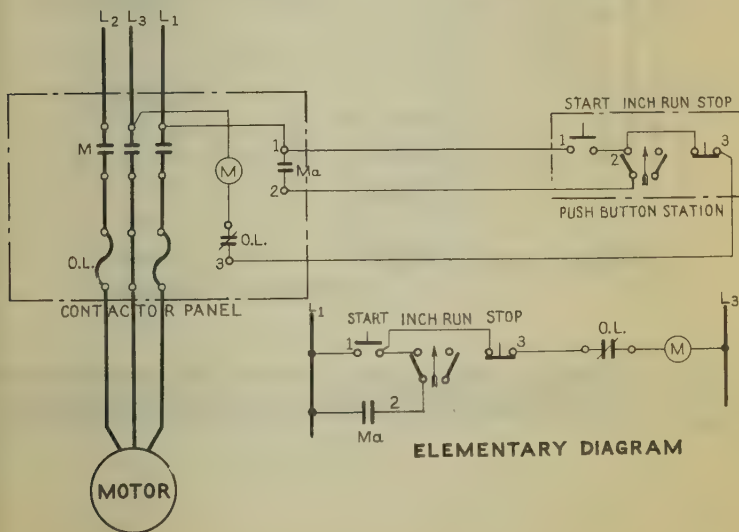
FIGS. 10 and 11.—Wiring diagrams illustrating wiring of push-button stations. The two push-button stations consist of four momentary control buttons, two of which are closed and two open. The circuit includes low voltage protection and the main contactor may be opened or closed, thus stopping or starting the motor from either one of the push button stations. In the diagram *M* indicates main contactor, *O.L.* overload relay, *Ma* main contactor interlock.

Limit switches have not been included in any of the diagrams, although they are frequently used. These switches are governed by the same rules that apply to push-buttons, that is, in most instances the push-buttons can be replaced by a limit switch. Switches normally closed are similar to stop buttons, and those normally open operate as start buttons. Momentary-contact limit switches which are spring-returned give low-voltage protection, and low-voltage release is had by maintained-contact switches.

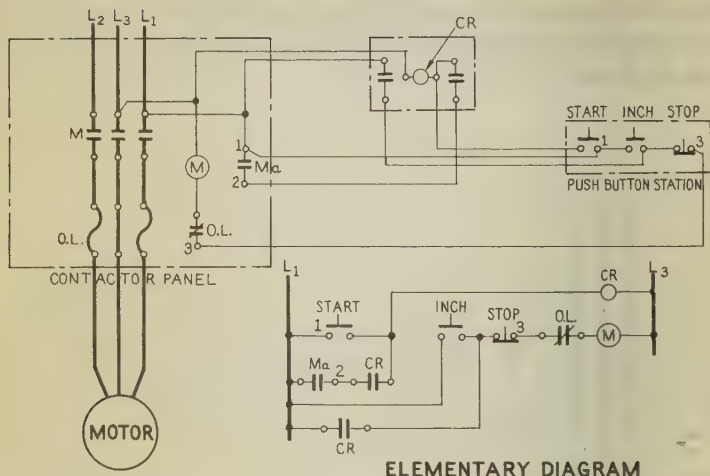


Figs. 12 and 13.—Wiring diagram illustrating wiring of push-button stations. The control feature is similar to that shown in the previous diagrams, except that the wiring between the two push-button stations contain only three wires instead of the usual four. This wiring scheme makes for a more economical wiring, especially where the distance between the two stations is of considerable length.

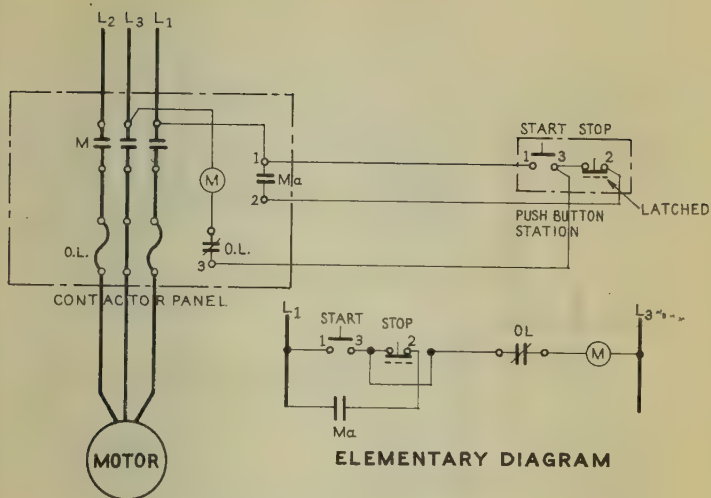
In the accompanying diagrams number 1 has been used to designate the control circuit to the start button; 2, the point common to the start-stop button, and 3, the stop button. On some controls manufactured currently these same markings are used to aid in making common push-button connections. The holding interlock parallels the start buttons; therefore, in the schematic diagrams it is connected to points 1 and 2, of the push-buttons.



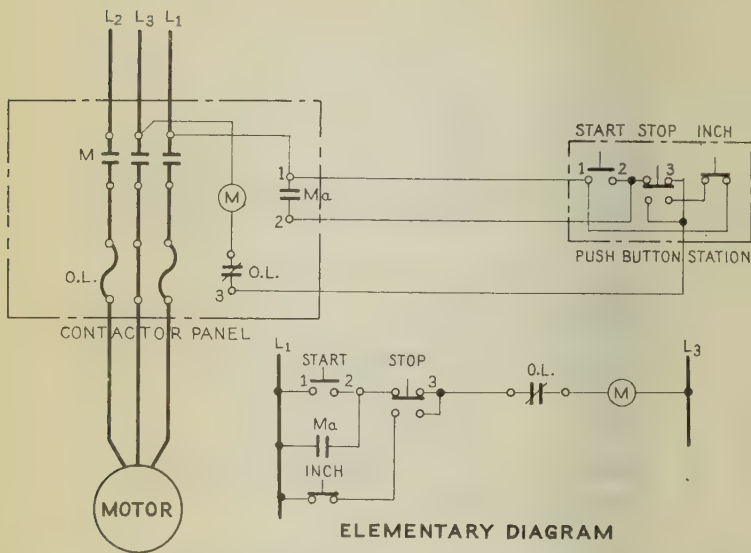
FIGS. 14 and 15.—Wiring diagrams illustrating motor control from one push-button station. The control station includes two momentary contact buttons and one selector switch. The circuit feature consists of low voltage protection plus inching. The push-button duty is: *Start-Run, Inch-Stop*.



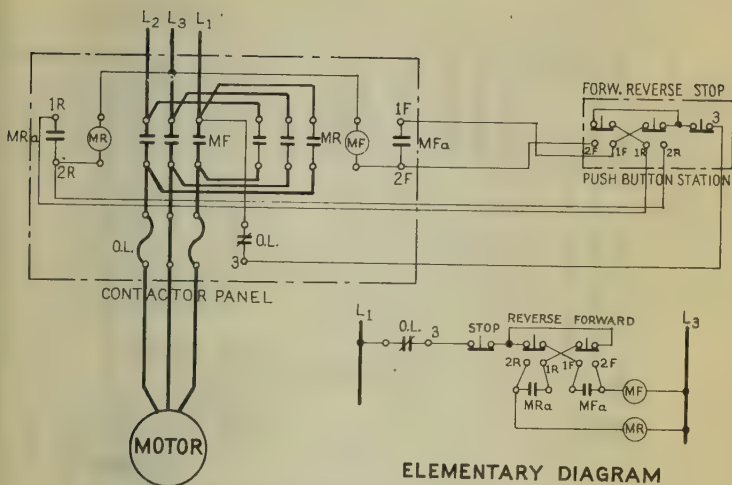
FIGS. 16 and 17.—Illustrating a push-button motor control circuit with a special inching relay panel. The control arrangement includes low voltage protection plus foolproof inching. Control circuits of this type are frequently employed in motor application where frequent inching is necessary.



Figs. 18 and 19.—Push-button motor control circuit with low voltage protection. The push-button control station includes two momentary contacts, one open, one closed. The closed button is equipped with a safety latch.

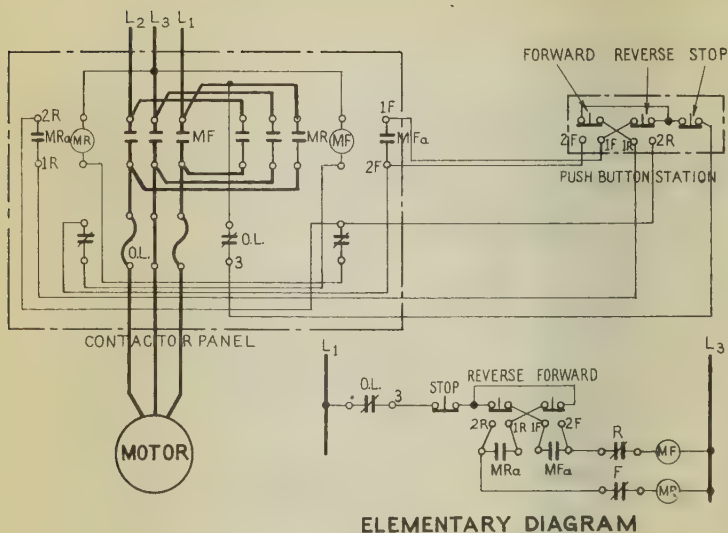


FIGS. 20 and 21.—Wiring diagrams illustrating motor control from a *Start, Inch and Stop* push-button station. The push-button station consists of three momentary contact buttons, two open and one closed. The circuit is wired for low-voltage protection plus inching which is obtained by holding down the stop button. The push-button duty is: *Start-Inch-Stop*.

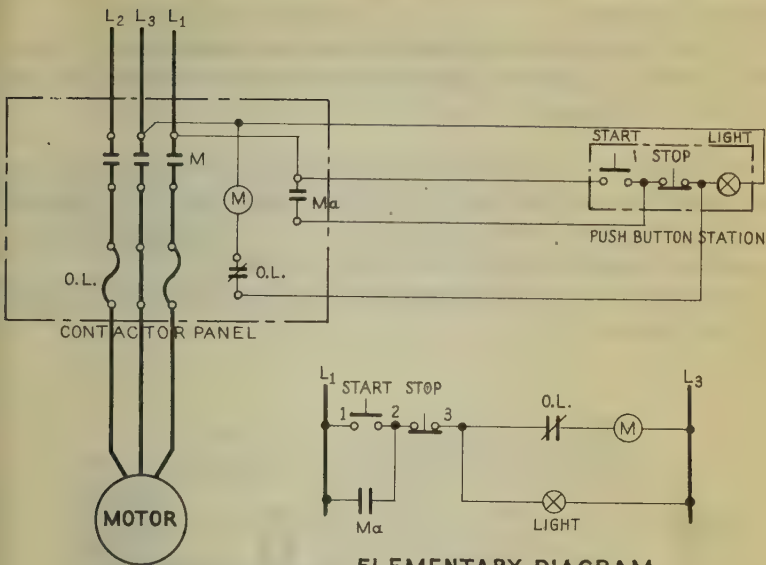


ELEMENTARY DIAGRAM

FIGS. 22 and 23.—Wiring diagrams illustrating motor control from a push-button station. The duty in this wiring scheme includes *Forward*, *Reverse* and *Stop*. The push-button station consists of three momentary contacts, two open and one closed. The circuit incorporates low-voltage protection with electrical interlocks.



FIGS. 24 and 25.—Push-button operated motor control. There are three momentary contact buttons, two open and one closed. The circuit provides low-voltage protection with electrical interlocks. The push-button duty is: *Forward, Reverse and Stop.*



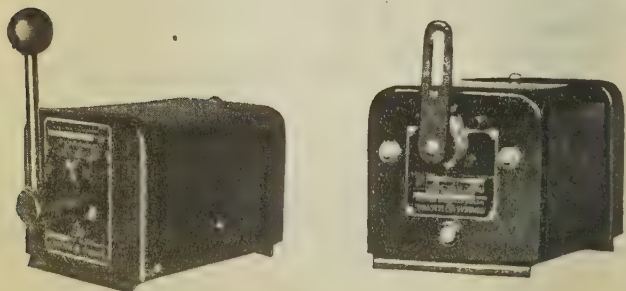
FIGS. 26 and 27.—Motor control circuit operated from a push-button station. The circuit incorporates low-voltage protection, and has a two momentary contact push-button, with indicating light showing position of contactor. The push-button duty is: *Start* and *Stop*.

Transfer Switches.—These are found in numerous control applications. The desired function is usually obtained by rotating the switch shaft by means of a handle mounted on the projecting shaft.

On the switch shaft are mounted several independently insulated cams, by means of which connections are made with the stationary contacts.

A switch of this type may perform the same function as that of a multi-blade knife switch, but is usually preferred because of its reduced space requirement due to its compact arrangement, and also because it is entirely enclosed.

External views of two typical rotating cam switches is shown in figs. 28 and 29.



FIGS. 28 and 29.—External view of two types of rotating cam switches. (Courtesy General Electric Co.)

Switches of this type are used for the full-voltage starting and controlling of squirrel-cage alternating current motors as follows:

1. Single-speed reversing.
2. Two-speed, non-reversing separate winding.
3. Two-speed, non-reversing, single winding.
4. Three- and four-speed with one speed reversing.

The switch frames are usually fabricated of strong steel plate and may be either machine or wall mounted.

Both the movable and stationary contacts are supported by strong moulded insulating material, each contact unit being separated by removable arc resisting barriers which confine all arcing.

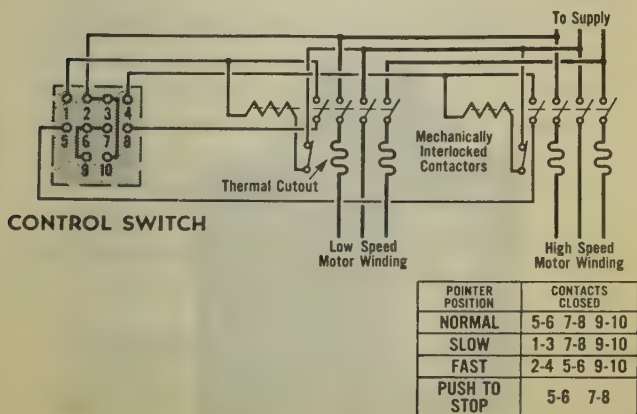


Fig. 30.—Connection diagram of two contactor speed control switch, for two-speed motor.

Solenoids.—Although solenoids are not a part of a motor control as we commonly understand it, many solenoids are included in industrial control applications.

Briefly, a solenoid consists of a stationary magnetic frame, a coil and a movable armature.

When the coil is energized, the movable armature is attracted to the frame and causes the armature to move so that it completes the magnetic circuit. By means of the solenoid, electrical energy is converted into straight-line motion.

Solenoids are used to open and close valves, in the operation of switching devices such as circuit breakers, relays, also as magnetic brakes on cranes and elevators, and on similar applications where a considerable pull with a minimum of travel is required. They are made for operation on both alternating and direct current circuits, and are widely used throughout the machine industry.

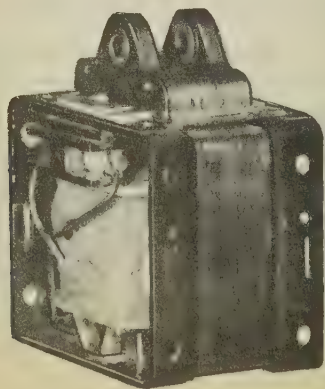


FIG. 31.—Showing external view of typical solenoid.

Electrically-Operated Valves.—These are used for controlling the flow of a liquid or gas through pipes from a remote point. They are usually operated from solenoids when the distance travelled by the valve stem in opening is relatively short or on small size valves where the pull is not too great.

These valves can be either normally open or normally closed, and are suitable for use directly on voltages up to 600 volts, alternating or direct current.

They are usually available in sizes of from one quarter inch up to twelve inches, and for use in operating pressures up to 400 lbs. at temperatures up to 700° F.

As solenoid valves inherently have less force available to operate them than have manually or motor-operated valves, they must be carefully selected.

The following rules should be noted when selecting a solenoid valve:

- (a) Select a valve whose internal construction is such that it will not become clogged by the fluid being controlled.
- (b) The valve should be constructed of materials that will not be chemically or mechanically affected by the fluid being controlled.
- (c) The valve should be of sufficient size to allow the flow desired.
- (d) Do not use a valve to control a fluid heavier than listed for a particular valve.

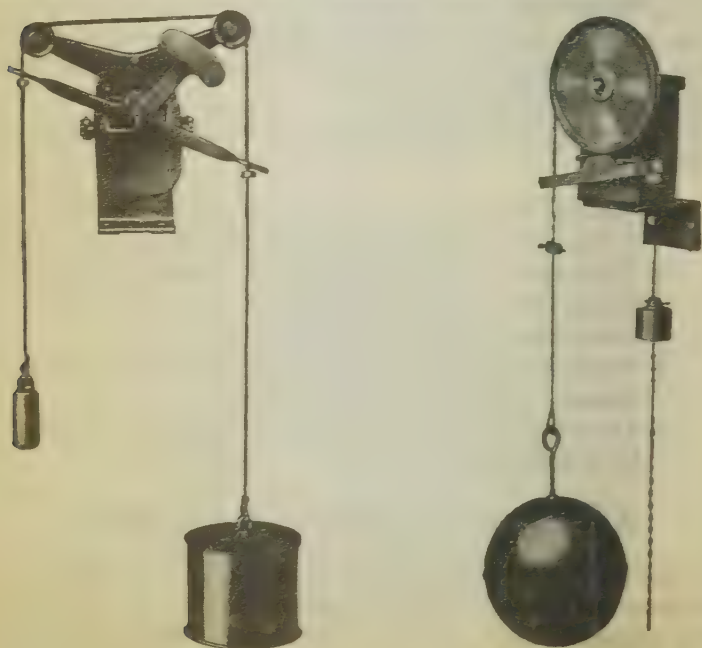
Automatic Control Switches

General.—In certain motor applications, it is desirable that the control itself shall operate the motor without any attendant being present. Such operations are usually found in various pumping applications, machine tool applications, etc.

The motor in such controls is usually actuated by means of switches, where the movement of a liquid or the driven machine may be used as the motivating force.

Other automatic control switches are those actuated by temperature or pressure of liquids or gases. An example of a switch of this latter type is found in compressor motors.

Float Switches.—Float switches are devices used to maintain predetermined high or low water levels in tanks or reservoirs in which water is discharged by motor driven pumps.



FIGS. 32 and 33.—Showing typical float switches.

Typical float switches of this form are shown in figs. 32 and 33.

These switches are arranged for tank operation, that is, the switch closes as the lower liquid level is reached, and opens as the top level is reached, in this manner starting or stopping the pump motor.

By reversing the operating mechanism, the float switch can be used to empty a sump. Switches of this type are usually available in single, two- and three-pole forms.

A float switch can handle a small motor on its contacts, but generally the contacts are used to handle the control circuits of a magnetic starter.

Various forms of mounting arrangements are used so that the float switch can be mounted on a horizontal plank lying across the top of the open water tank, or it can be hooked over the side of the tank at the top with a hook-on clamp. Either rod or chain operated switches are used.

Water levels in tanks or sumps can be maintained over a range of from a couple of inches to many feet.

With reference to fig. 32, the switch float is hung from one end of the chain and the counterweight from the other end. It is important that the counterweight and the float be correctly proportioned for operation of the switch.

In most applications the float has a weight twice that of the counterweight which it supports. Also the float must be buoyant enough to float with about half of its volume submerged in the liquid.

The material of the float is usually copper, and in order to supply the necessary stability in operation, it is commonly weighted down with cast iron.

It is evident that a large diameter float is more sensitive to change in the liquid level than that of a small diameter float.

With modern float switches, it has been found that the average diameter of the float should be from 6 to 8 inches for satisfactory operation.

Pressure Switches.—These are used to maintain a desired pressure in a closed system containing a liquid or vapor.

The actuating part in a switch of this type usually consists of a metal bellows or diaphragm, an operating linkage system and a lever adjustment spring. The diaphragm expands or con-

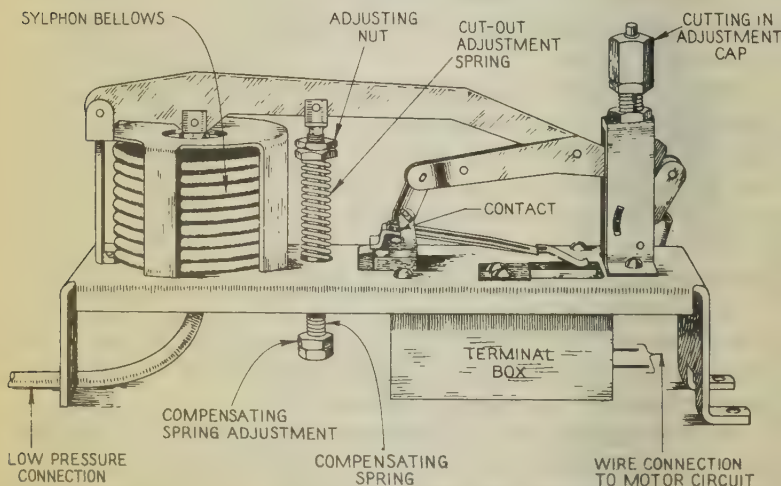


FIG. 34.—Typical low pressure control switch as employed in a refrigerating system. This particular switch consists essentially of a sylphon bellows, an operating linkage system and a lever adjustment spring. The bellows expand or contract, due to the difference between the pressure of the refrigerant inside and the atmospheric pressure outside the bellows. When the pressure on the low side increases due to the rise in the refrigerant temperature, the increased pressure conducted through the tubing, causes the bellows to expand. This expansion is transmitted through the leverage arm (controlled by the springs) which closes an electrical contact, thus completing the motor circuit, starting the motor and compressor. When the temperature and consequently the pressure, reaches the cutting-out point as set by the adjusting nut, the bellows contracts, causing the switch to open the circuit, disconnecting the motor from its supply source, thus stopping the compressor.

tracts due to difference in the pressure of the liquid or vapor inside and the atmospheric pressure outside the diaphragm.

When the pressure in a compressed air tank for example, falls to a predetermined minimum, the pressure on the switch diaphragm is reduced to a point where a set of contacts are actuated, thus starting the motor compressor. When the pressure reaches a predetermined maximum value the diaphragm in the switch opens the contacts and the compressor is shut down.

One of the most common applications of the pressure switch is on a garage compressor. A pressure switch may also be used to maintain the water level in a closed tank by providing a certain amount of air within the tank, the pressure of which varies directly with the water level.

Pressure switches can handle small motors directly, or the pressure switch contacts can be used to actuate the control circuit of a magnetic starter.

Temperature Switches.—Switches of this type (also called *thermostats* or *thermostatic control switches*) are manufactured in a number of forms.

The most well-known of these are the bimetallic switch type where two metals of different co-efficient of expansion changes its convexity with variations in temperature, and in this manner actuates a set of electric contacts.

Other types depend upon their functioning on a metal bellow or bellows and a capillary tube. A typical switch of this latter type used in refrigeration work is shown in fig. 35, the operation of which is as follows:

The gas, with which the thermostatic element is charged, is very sensitive to temperature changes. A rise in temperature at the bulb is accompanied by a corresponding rise in gas pres-

sure, which elongates the bellows. This movement of the bellows is transmitted through its hardened cone-shaped pivot, to the main operating lever, which through its linkage, tilts the mercury switch to an "on" position. As the temperature of the bulb and gas within it drops, this is accompanied by a drop in gas pressure. The main adjustment spring acts against the bellows pressure, then reverses the action of the main lever and tilts the mercury switch to an "off" position.

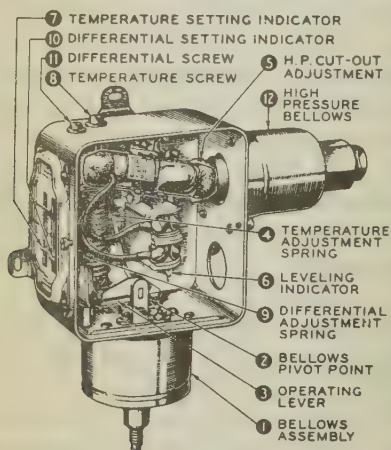


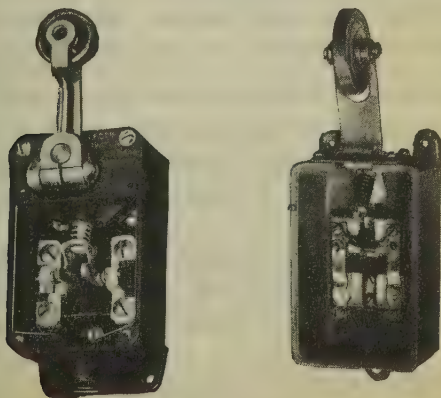
FIG. 35.—Showing construction of a typical temperature control switch.

The cut-out temperatures are constant for any particular setting of the main range adjustment. The differential adjustment regulates the difference between the cut-out and cut-in temperatures and is adjustable within the limits shown. The differential lever and spring acts to impose additional loading on the main lever, thereby raising the cut-in point to a value proportional to the tension of the differential spring. The

action of the differential mechanism is, therefore, independent of the cut-out point temperature, as a change in the differential does not change the cut-out point.

The high pressure cut-out element of the switch is connected to the high side of the compressor. When the pressure rises to a dangerous point, the bellows compresses and tilts the mercury switch to an "off" position. As the pressure decreases, the spring within the bellows asserts its action to return the bellows to a normal position and tilt the mercury switch to an "on" position.

Limit Switches.—Switches of this type are generally used to limit or indicate the travel of some moving part of a motor driven machine or apparatus.



FIGS. 36 and 37.—Showing construction principles of two lever type limit switches. (Covers removed.)

The contact mechanism is usually equipped with either normally open or normally closed contacts. The most generally used is the so-called lever type in which the contacts are operated from a lever that extends out from the main part of the limit switch. On the end of this lever is a roller. The moving part of the machine comes in contact with the roller and moves it to such a position that the contacts in the limit switch are either open or closed. Some typical applications of lever type limit switches are at the top and the bottom of a dumb-waiter, skip hoist, motor-driven roller door, or motor-operated windows. If applied to a door, when the door reaches the extreme or open position, some part of the door comes in contact with the limit-switch roller; the limit-switch contacts are opened; this opens the control circuit to a magnetic controller, and the motor is stopped. In closing the door, the motor is started by means of the push-button in the reverse direction, and when the door reaches the closed position, a second limit switch is operated and the motor is stopped.

Plugging Switches.—These switches also known as *friction switches* are frequently used in operations where it is desired to obtain *quick stopping* by reverse power or *plugging* in connection with A.C. controllers or for reversal when a motor has reached zero speed.

Switches of this type are of various design, some are provided with a loose pulley suspended belt, while others have closely mounted discs immersed in oil, supplying the necessary actuating force.

A typical plugging switch is shown in fig. 38. This switch has the contacts so arranged that they will open or close when the speed of its driving shaft approaches zero, or when a definite increasing speed is reached. Control with speeds in either direction may be obtained by using two sets of contacts. These

contacts can be arranged for two separate functions, each depending upon the direction of rotation of the control shaft.

The switch is provided with a safety latch to prevent closing of the contacts when the switch is turned by hand.

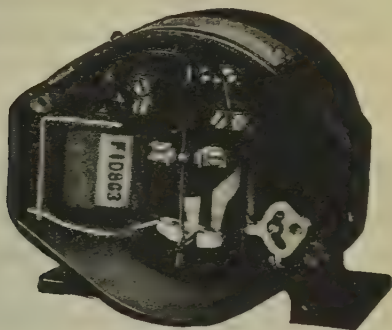


FIG. 38.—Typical plugging switch, with cover removed to show construction. (Courtesy General Electric Co.)

Rotating Cam Switches.—As the name implies, operation is here obtained by the rotation of the switch shaft, which in turn rotates one or several independent cams to actuate the contacts.

These are used in numerous control or transfer operations and are usually provided with a projecting shaft with a general connection to the machine or apparatus whose operation is to be controlled.

A typical rotating cam limit switch used for machine, mill and hoist service control is shown in fig. 39. This switch provides for the control of ten independent circuits, and is adopted for continuous operation in either the clockwise or counter-clockwise direction. It is made with a cast iron frame and provided with a sheet steel cover.

For satisfactory operating life, the speed of the driving shaft should be between 5 and 60 *r.p.m.* with allowance for gear reducer.

In this particular switch, operation is obtained by rotating the shaft, which rotates a series of independent molded cams to operate the contacts. The contact is closed by the closing cam or dog and remains closed until operated by tripping dog.

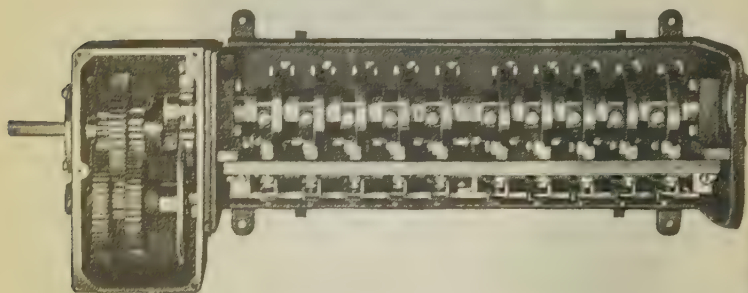


FIG. 39. Showing a typical rotating cam switch with gear reducer. (Covers removed.)
(Courtesy General Electric Co.)

Selection of Control Wire Size.—Although in most contactor and relay operations a 20% voltage drop is allowed, it is important that control wires be so selected that this maximum drop under all conditions not be exceeded.

Therefore, in remote operations of controls, it is often desirable to know the allowable length and size of a conductor that can be used between the remote operating point and the controller. These calculations differ for alternating and direct current circuits, in addition to being affected by capacity, as well as inductance from adjacent conductors. Under ordinary

circumstances, however, these factors need not be considered unless the control line is of considerable length.

Direct current contactors and relays are generally designed to pick up at 80% coil voltage when hot. This means that if 100% control circuit voltage is available, theoretically a 20% voltage drop can be tolerated in the conductor in series with the coil, and the device will still operate. To allow a factor of safety, because of varying operating conditions, a 10% drop in the control wire is a safer value to use. On this basis, using Ohm's law, we obtain:

$$R = \frac{0.1 \times E}{I}$$

Where R = conductor resistance in ohms.

I = pick-up current of contactor or relay coil in amperes.

E = normal operating voltage of contactor or relay coil in volts.

On alternating current contactors and relays, however, the inrush current required to close the magnet is much higher than the normal circuit after the magnet has closed. Therefore, the formula previously shown cannot be used. In numerous applications it is found that the resistance in series with the coil can be as much as 25% of the total ohmic resistance of the coil.

If the resistance of the coil be not known, it can readily be obtained by energizing the coil on direct current, and by measuring the voltage across the coil and the current flowing through it.

Then the unknown coil resistance is:

$$R = \frac{E}{I}$$

This resistance cannot be measured by an application of alternating current.

Now any wire table can conveniently be used to determine the minimum size of copper wire after the ohmic resistance has been obtained by either of the two methods previously given.

In many applications it will be found that this minimum size is impractical from the standpoint of mechanical strength.

In such cases, a wire should be selected large enough to fulfill in addition to electrical requirements, mechanical requirements as well. This latter requirement is an important consideration especially when it be required that the wire be strung out of doors on poles where it is often subjected to the strain of wind, sleet or snow.

Magnetic Brakes

General.—By definition magnetic braking is a system of electric braking in which brakes are applied by magnetic force, the current for exciting the electro-magnets being derived either from an independent source, or from the traction motors, acting as generators.

The function of magnetic brakes in industrial applications is to stop the motor or apparatus quickly and accurately. They are also employed on cranes, hoists, and similar machines to hold the load after a stopping of the motor.

There are three main types of magnetic brakes which are, according to their construction, classified as:

1. Band.
2. Multiple disc.
3. Shoe.

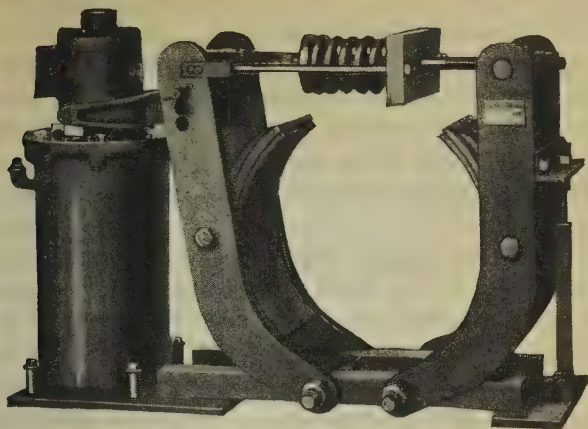


FIG. 40.—Illustrating a typical thruster operated alternating current spring-set shoe brake.

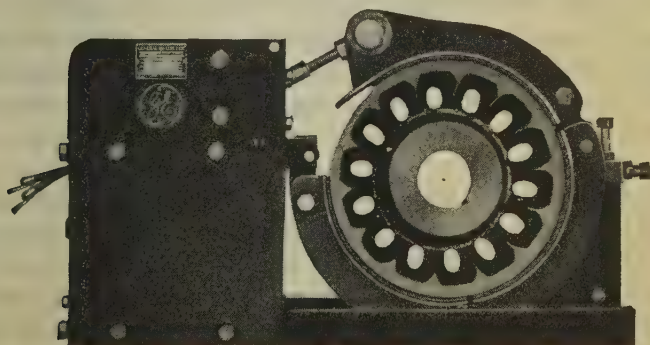


FIG. 41.—Showing a typical magnetic direct current spring-set three-shoe brake.

The most common type of band brake has a wheel attached to the shaft to be braked and this wheel is partially or wholly encircled by a band lined with friction material. Normally the band is brought into frictional engagement with the wheel by means of a spring or springs; a solenoid is provided for the purpose of compressing these springs and relieving the brake band. Band brakes are designed for use for either alternating or direct current.

The multiple disc type of brake consists essentially of a hub which is mounted on the shaft to be braked; to the hub are keyed one or more discs and a stationary disc. Normally the rotating discs are clamped between the stationary disc by the action of a spring, and by means of an electromagnet this spring can be compressed and the pressure on the friction discs relieved. The multiple-disc brake is manufactured only for direct current service.

The shoe brake differs from the band brake mainly in that the movable friction face is in the form of a shoe rather than in the form of a band. These types of brakes are manufactured for both alternating and direct current service. Fig. 40 illustrates a typical alternating current spring-set thrustor operated shoe brake and fig. 41 shows a typical direct current solenoid operated three-shoe brake.

Advantages of the Various Types.—The choice of a certain type of brake depends upon several conditions, such as the type of electric service available, the service of the motor to be braked, the space available for the brake, the cost of the installation, etc. Generally the disc brake has a certain advantage over other types in that it imposes no side strains on the shaft to which it is applied. It also provides equal braking for either direction of rotation, whereas certain forms of band and

shoe brakes do not provide this feature. The band type of brake generally has a certain advantage over the shoe type, because of the larger proportion of the brake wheel which is in actual service, and the consequent reduction in the unit pressure of braking surfaces.

The modern type of shoe brakes, however, are very largely used because of their ease of adjustments, their smooth action, and protection of the braking surface from foreign matters and because a protective steel housing encloses the entire operating mechanism.

Brake Size.—Since brakes are most commonly rated on the *torque basis*, that is, the torque they can deliver over a specified period of time, it is necessary to determine the full-load running torque of the motor or shaft to which the brake is to be applied.

This may be determined by the use of the following formula:

$$\text{Torque in lb. at 1 ft. radius} = \frac{\text{Horsepower} \times 5,252}{\text{Full load } r.p.m.}$$

Any brake should have a torque above or equal to that obtained from the formula. Standard ratings for *service brakes* are 0.25 hour 0.5 and 1 hour and continuous. For shunt brakes the rating is either intermittent or continuous.

Usually a series-wound brake can be used on applications where the motor current does not fall below 10% of the full load current of the motor. If the current falls below this value, or a drift point is desired, a shunt-wound brake should be used. Series-wound brakes are standard for all crane and hoist work.

A basic direct-current three-shoe brake, as shown in fig. 41, is designed for holding loads and stopping motor armature and gears, but is not suitable for lowering or stopping loads (except as auxiliaries to mechanical load brakes) or for dynamic-braking

or plugging control. Shunt-wound brakes are usually designed to operate on 85% of voltage.

Series-wound brakes are usually designed to release on 40% of the rated current of the motor with which they are used, and will remain released on 10% of rated motor current. Release at 40% current is considered necessary for use with dynamic braking control. A type of the design, shown in fig. 41, may be mounted in any position and on any firm support available.

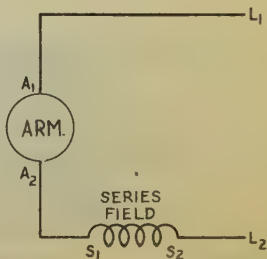
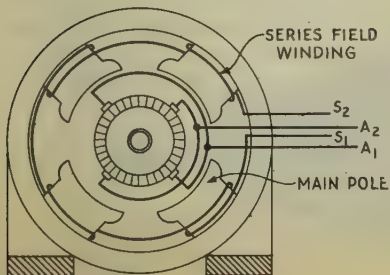
CHAPTER 7

Direct Current Motors

Classification.—Direct current motors are classified according to the type of winding employed as:

1. Series-wound.
2. Shunt-wound.
3. Compound-wound.

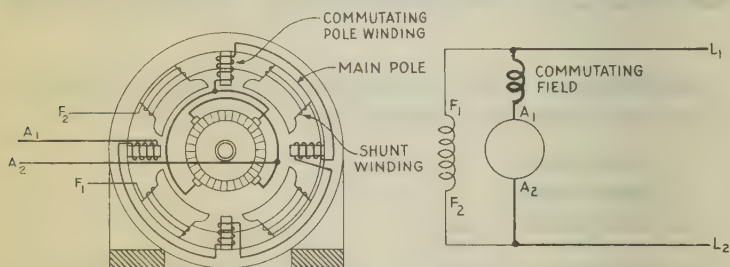
The series-wound motor, figs. 1 and 2, as the name implies is one in which the field coils and armature are connected in series and the entire current flows through the field coils.



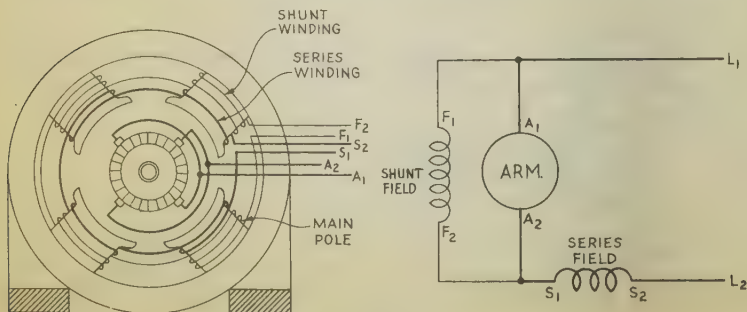
FIGS. 1 and 2.—Wiring diagrams showing connections for series-wound direct current motor.

The shunt-wound motor, figs. 3 and 4, has derived its name from the fact that the field coils and the armature are connected in *shunt* (parallel) and because of this, the field current is only a small portion of the total or line current.

Again, the compound wound motor, figs. 5 and 6, incorporates both the *series-wound* and the *shunt-wound* motor types of winding, that is, it has both the series and the shunt winding previously illustrated.



FIGS. 3 and 4.—Wiring diagrams showing connections for shunt-wound direct current motor with interpoles. The interpoles (commutating poles) are in series with the armature so that their field strength will be proportional to the load of the motor.



FIGS. 5 and 6.—Wiring diagrams showing connections for cumulatively compound-wound direct current motor.

Direct Current Motor Construction.—All direct current motors regardless of size have a stationary field member, usually called frame or yoke, and a rotating armature member, fig. 7 and 8.

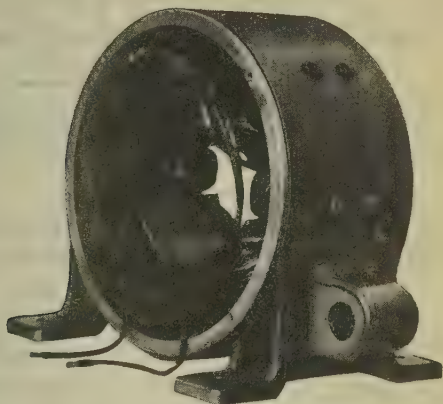
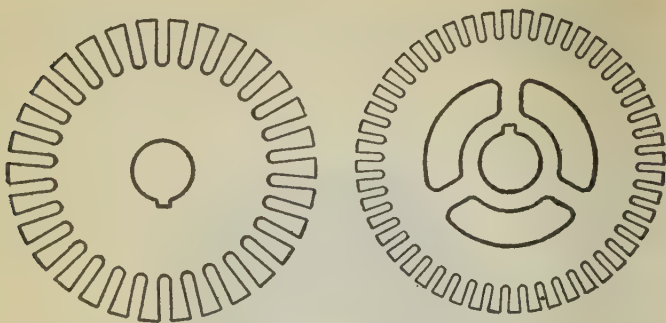


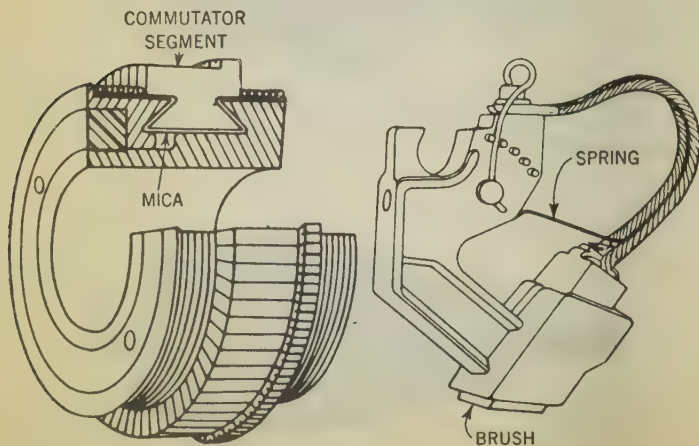
FIG. 7.—Illustrating the field of a direct current motor with interpoles or commutating poles between the large main poles.



FIG. 8.—Armature of direct current motor.



Figs. 9 and 10.—Solid and ventilated core discs. The metal cut-away at the center, fig. 10, reduces weight and provides for air circulation through the armature.



Figs. 11 and 12.—View of commutator and brush arrangement.

The frame is made of cast or fabricated steel and serves as a means of support for the motor and forms a part of the magnetic circuit connecting the field poles and commutating poles with the line, armature and brushes.

The brushes are constructed as a means of carrying the current from the external to the internal circuit. They are usually made up of carbon and are carried in brush holders, which are mounted on brush-holder studs or brackets.

The field poles upon which the field coils are wound are made up of cast steel, forged steel or steel laminations. When cast or forged steel is used, the cores are usually made with a circular cross-section. The laminated pole construction which is most commonly used, except for very small motors, have a rectangular cross-section and are fastened to the frame by bolts.

The armature, fig. 8, is made up of machine wound coils embedded in parallel slots on the surface of the armature core. The core is made up of stampings of thin wrought iron or mild steel stampings of from about 18 to 25 mils in thickness.

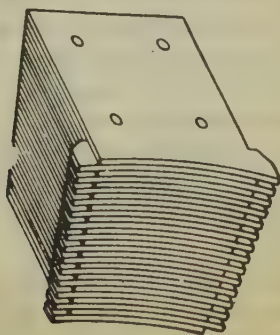


FIG. 13.—Typical field pole (laminated type) showing method of assembly.

The commutator is built up of segments of hard-drawn copper insulated from the supporting rings by "built-up" mica to form a cylinder, which are tightly clamped together by means of a heavy external ring. The number of commutator segments equals the number of armature conductors divided by an integer.

In order to improve commutation, modern motors are equipped with *auxiliary* poles, variously termed *interpoles* or *commutating* poles. They are small auxiliary magnet poles placed between the regular field poles. The purpose of these poles is to assist commutation and prevent sparking at the brushes for different loads.

Operating Characteristics

Series Motors.—The load characteristic curves of a series motor is given in fig. 14. A study of the current torque curves indicates that the torque varies approximately as the square of the armature current. From this, it follows that this type of motor is suitable in load application where it is necessary to supply a large torque with a moderate increase in current, such as in traction work, crane operation, etc.

The speed of a series motor, as indicated, varies greatly with the change in load. Because of this speed characteristic and the resultant possibility of dangerously high speed at light loads, this motor is not suitable for belt drive or for use on any loads where the torque might drop below 15% of full load torque.

Shunt Motors.—From the characteristic curves of a shunt motor, fig. 15, it follows that this motor will run at very nearly the same speed at any load within its capacity, and will not slow up very much even when greatly overloaded.

There is but a slight drop in speed from no-load to full-load.

This drop may vary from 5 to 15% of full-load speed, varying with saturation, armature reaction, and brush position.

Because of commutation limitations, shunt motors in integral horsepower sizes are not suitable for across the line starting.

Shunt motors designed for operation over a given speed range by field control, are not technically shunt motors, in that

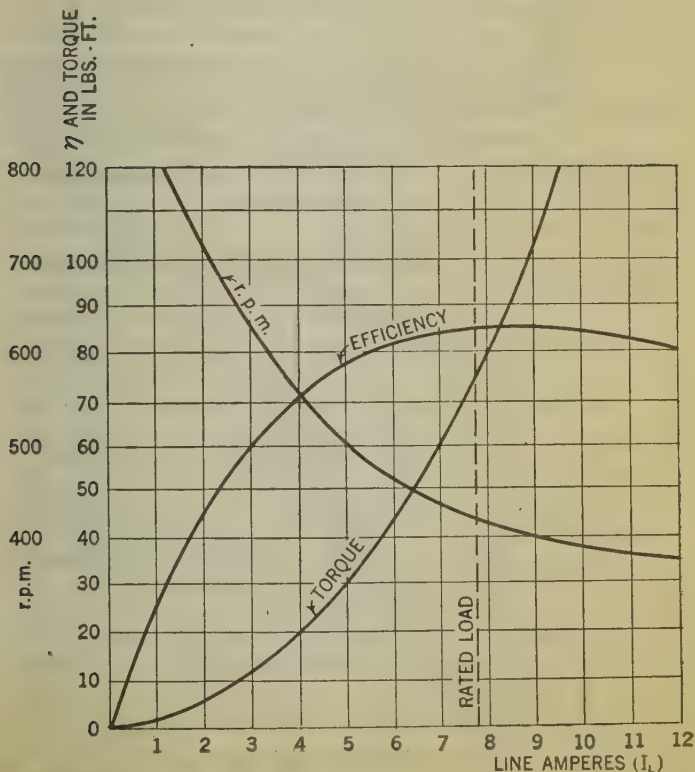


FIG. 14.—Operating characteristics of a series motor.

a stabilizing series field is added to assure stable speed under weak field conditions. When this winding is included, the possibility of armature reaction demagnetizing the weakened shunt field with change in load is eliminated.

Shunt motors without speed control are used to drive machinery that is designed to run all the time at the same speed.

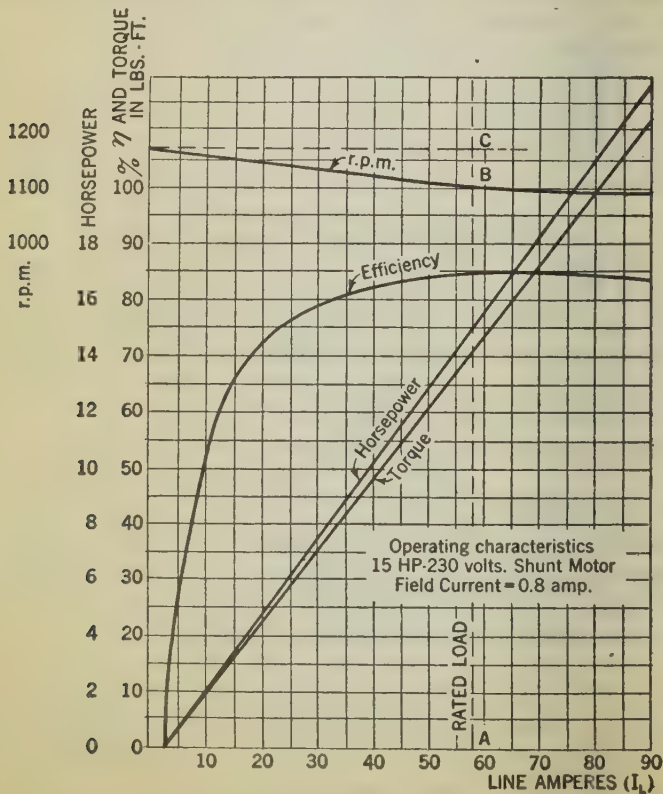


FIG. 15.—Operating characteristics of a 15 h.p. 230-volt shunt motor.

Compound Motors.—The addition of a cumulative, series field winding to the shunt field produces a compound motor.

The addition of this series field winding gives the motor a characteristic which is a combination of the series and shunt motor.

The speed changes with the load, but it does not change as much as in a series motor and it usually changes a great deal more than that of a shunt motor. Like the series motor, it has excellent characteristics for starting heavy loads and yet is in no danger of “running away” at light loads when used without a speed controller.

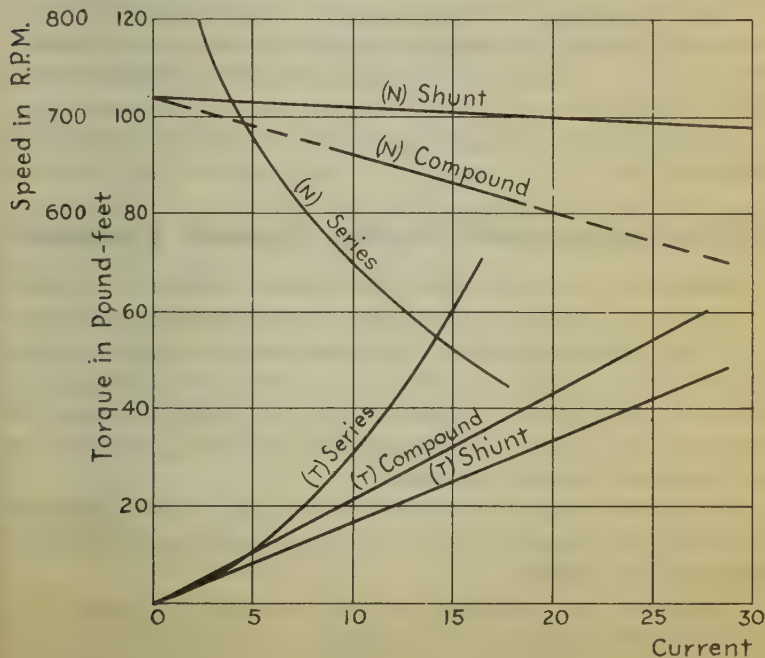


FIG. 16.—Speed-torque characteristics for compound, shunt and series motor of equal size.

Compound motors are used for loads requiring high starting torque, or on loads subject to torque pulsations. They are not practical for applications requiring adjustable speed by field control. With weakened shunt field, the series field flux becomes a greater portion of the total flux; hence the changes in load may produce unstable speed.

Compound motors are commonly employed for elevators, air compressors, ice machines, certain kinds of hoisting and conveying machinery, printing presses, paper cutters, pumps and other machinery where the load fluctuates suddenly or periodically, and where constant speed is not essential.

They are usually designed so that there will be a drop in speed of about 20% between no load and full load. Compound motors may be wound for greater or less speed change to meet special conditions.

In sizes up to 5 *h.p.*, they are usually wired for across the line starting.

Direct Current Motor Speed Control

General.—The factors which determine the speed of a motor are the voltage across its armature and the strength of the field.

If the voltage supplied to the armature be reduced to one-half its original value, the speed of the motor will be reduced in the same proportion. Similarly, if the voltage across the armature be doubled, the speed will be doubled, provided the field strength remains the same.

Also, if the magnetic field be weakened, the motor speed will increase and conversely if the field be strengthened the motor speed will be reduced.

There are four principal methods whereby the speed of a direct current motor can be regulated. They are:

1. Shunt field control.
2. Armature resistance control.
3. Variable voltage control.
4. Multi-voltage control.

Shunt Field Control.—It has previously been pointed out that a weakening of the field *increases the speed of a motor*, and a strengthening of the field *decreases the speed*.

This method of varying the field strength by means of a variable resistance inserted in series with the *shunt field* is most commonly used as a means of speed control for direct current motors. By this method the speed of a shunt motor may be varied from normal to four times normal, depending largely upon the mechanical construction of the motor.

It is not practical generally to build adjustable speed motors for a range exceeding four to one as the shunt field becomes so weakened that the characteristics of the motor assumes more the shape of heavily compounded motor curves rather than shunt curves. A schematic connection diagram showing this method of speed control is given in fig. 17.

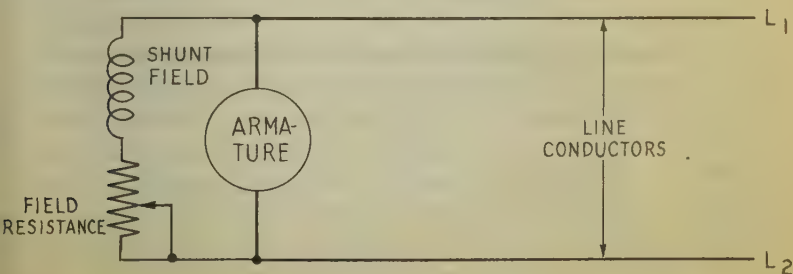


FIG. 17.—Diagram showing speed control of a direct current motor by means of a resistance in series with the field. The speed of the motor will vary in proportion to this resistance. An increase in resistance reduces the shunt field current and gives a higher speed, and conversely a decrease in resistance increases the shunt field current and gives a lower speed.

The variable field resistance may be a simple field rheostat or it may be combined with a starting rheostat.

Shunt motor speed control by means of a variation in field resistance is most satisfactory and efficient. The wattage loss (I^2R) in the field circuit resistance is small since the field current is small compared to the armature current.

This method of speed control is also used for compound motors, although for any speed setting there is some variation in the speed with load, in contrast to the shunt motor where the speed is but slightly affected by the load.

For speed control of series motors this method is often applied although in a modified form. Here it consists in shunting part of the current around the field coils, thus weakening the magnetic field and increasing the speed of the motor.

Armature Resistance Control.—The speed of a direct current motor may be *decreased* by inserting a resistance in series with its armature as shown in fig. 18. The speed at full load may be decreased to any desired value, depending upon the amount of this resistance.

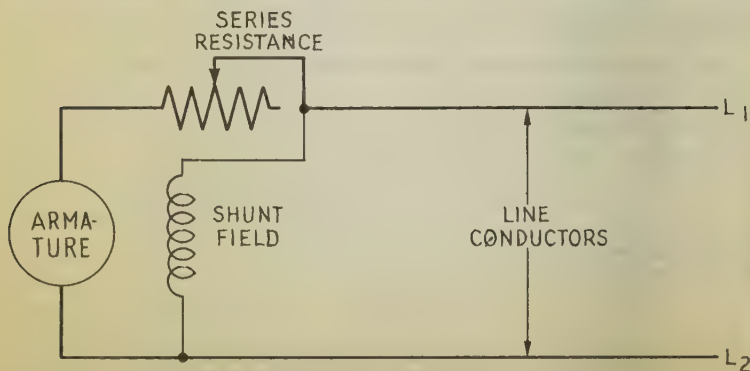


FIG. 18.—Connection diagram showing speed control of a direct current motor by means of a resistance in series with the motor armature. An increase of this resistance gives a lower speed.

Here the armature voltage drops as the current passes through the series resistance, and the remaining voltage applied to the armature is lower than the line voltage, thus the speed is reduced in direct proportion to this voltage drop at the armature terminals.

For example, if at full load an amount of resistance is inserted so that one-half of the voltage is consumed in the resistance, the motor speed will be reduced to one-half.

In the case of a 220-volt motor with an armature current of say 50 amperes, and a series resistance of 2 ohms inserted in the armature circuit, the voltage drop would be 2×50 or 100 volts. In this case 120 volts would be applied to the armature and the resulting speed reduction would be $120/220$ or 55% of normal speed.

The wattage loss (I^2R) in this case would be $50^2 \times 2$ or 5,000 watts.

If on the other hand the armature current were only 25 amperes, all other factors remaining the same, then the voltage drop would be 25×2 or 50 volts. The voltage applied to the armature $220 - 50$ or 170 volts, and the speed of the motor $170/220$ or 77% of normal. The wattage loss in this latter case would be 1,250.

Thus, it will readily be observed from the examples shown that this method of speed control is inefficient and costly, since a large proportion of the energy to the motor is dissipated in heat. An additional factor is that it is sometimes difficult to dissipate this heat and the regulation is very poor.

Standard speed controllers are commonly made to reduce the speed 50% when full-load current is flowing through the armature. If only half the full-load current be flowing through the armature, the speed will be reduced only about 25%.

Variable Voltage Control.—This system of speed control requires a generator for each motor, the motor field being maintained constant while its armature voltage is varied by varying the generator field strength.

This method gives a large speed range with any desired number of speed points. It is essentially a constant torque system as the horsepower delivered by the motor decreases with a decrease in applied voltage and corresponding decrease in speed.

This particular system has a further advantage that can be used to provide excellent starting characteristics by bringing the generator voltage gradually up from zero, starting and bringing the motor up to speed with a comparatively slowly increasing voltage. Because of the excellent starting characteristics this system is used largely for modern high speed elevators, and on account of the combination of excellent starting characteristics and the wide speed range available, it is used to some extent for reversing planer installations. It is not applied to any great extent generally on account of the expense of the generating equipment.

Multi-Voltage Control.—The multi-voltage system consists of a generating plant or system so arranged that a number of different voltages may be applied to the armature of a motor whose field is connected across one voltage as illustrated in fig. 19. With reference to fig. 19, six different voltages may be obtained.

By means of a suitable controller any one of the voltages may be supplied to the motor armature terminals while the shunt field is connected directly to the outside line wires. Since the speed of the motor is direct proportional to the voltage impressed on the armature terminals, a variety of motor speed may thus be obtained.

Due, however, to the high cost of the power generating machinery, and current carrying conductors, this type of motor speed control is seldom used. With modern commutating pole motors a more economical speed range may be obtained by the common field resistance control previously described.

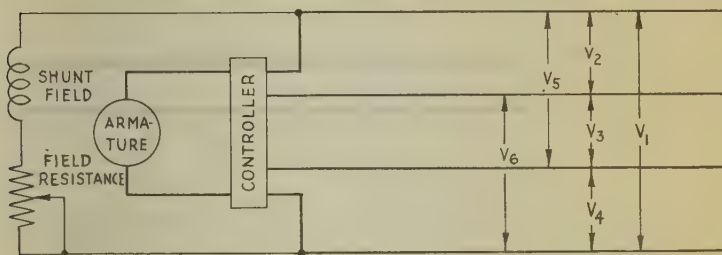


FIG. 19.—Showing multi-voltage speed control of direct current motor. The various voltages shown are usually obtained from a "balancer set." Due to initial high cost and complications, this method of speed control is seldom used. With modern interpole motors a more practicable form of speed control is obtained by means of field rheostat control as shown in fig. 17.

Ward-Leonard Speed Control System.—This system of speed control, fig. 20, utilizes a motor-generator set comprising a direct current generator supplying current to a shunt motor connected as indicated. Here the field circuit of the generator is supplied from the main circuit and has a field rheostat with sufficient resistance to vary the field current from its full value to nearly zero.

The drive motor whose speed it is desired to regulate has its armature connected to the variable voltage generator while its field current is supplied from the main line.

With this arrangement any speed of the drive motor from full value to nearly zero, may be obtained by adjustment of the generator field current.

On account of the cost of the machinery involved (three full-size machines required instead of one) it is utilized only when the required range and precision of speed adjustment cannot be obtained by a more economical method.

It is used to some extent in the operation of large printing presses, in gun turrets aboard battleships, etc.

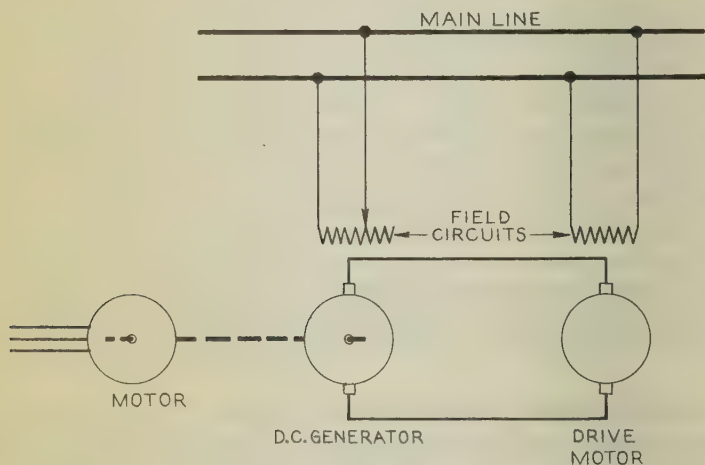


FIG. 27.—Schematic illustration of Ward-Leonard method of speed control for a direct current motor.

Special Adjustable Speed Motors.—Another method of motor speed control is obtained by changing the air gap (field flux) between the poles and the motor armature. In some motors of this type the field cores are geared together at their outer ends so that they may all be moved simultaneously in or out by means of a gear mechanism and handwheel.

In others the armature and the field poles are slightly tapered and the armature is shifted along the shaft by a gear mechanism. In both methods the speed is varied by adjusting the air gap.

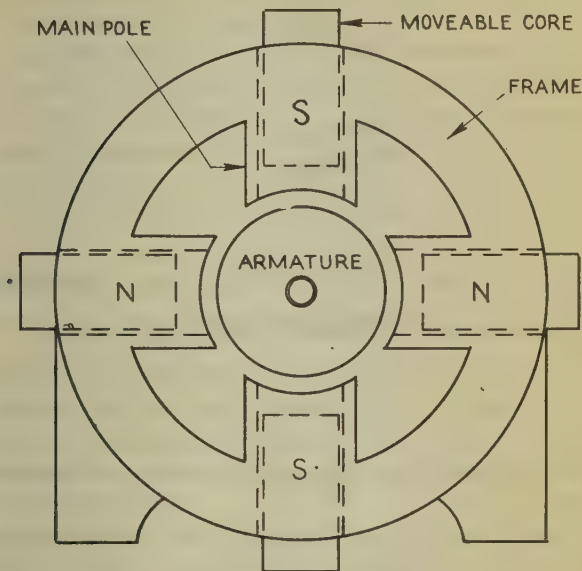


FIG. 21.—Diagrammatic representation of speed control by means of adjustable air gaps between the field core and armature.

An increase in speed is obtained by a lengthening of the air gap (weakening of the field) and a decrease in speed can be had by a shortening of the air gap (strengthening of the field).

This method (which is but another adaptation of speed control by field manipulation) is seldom used mainly on account of high construction cost.

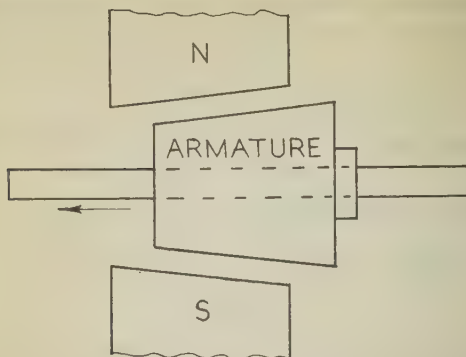


FIG. 22.—Diagram showing another method of speed control. Here a change in reluctance of the magnetic circuit is obtained by moving the armature axially as indicated.

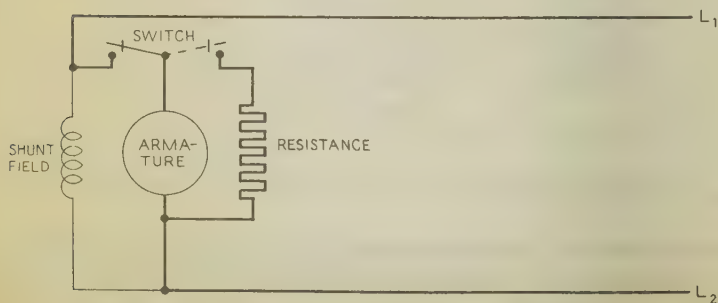


FIG. 23.—Diagram showing dynamic brake connections as applied to a shunt motor.

Dynamic Braking.—With reference to fig. 23, dynamic braking of a shunt motor is accomplished by inserting a resistance in parallel with the armature, as shown.

When dynamic braking of the motor is desired, the armature is disconnected and immediately connected to the “off” or “brake” position, placing the resistance bank directly across the armature terminals.

The rotation of the armature under the influence of the excited shunt field causes a voltage to be generated sending current through the resistance. As a result the motor functions as a loaded generator and develops a retarding torque which rapidly slows down the motor bringing it to a standstill. For typical dynamic braking control circuits see figs. 41 to 49.

Theory on Direct Current Motor Speed Control

General.—Hitherto direct current motor speed control has been discussed without any reference to the theory involved.

For those who are acquainted with simple mathematical expressions or formulas, a better understanding of this interesting subject is possible.

The expression for the torque (T) in any direct current motor is proportional to the armature current (I_a), the resultant flux per pole (ϕ), and a constant. It is written:

$$T = K\phi I_a \quad (1)$$

The value of the constant K depends upon:

- (a) the number of poles;
- (b) the number of armature conductors;
- (c) the type of winding used, and
- (d) the units in which the various units are expressed.

For a shunt motor such as that shown in fig. 24, applications of Ohm's law to the circuit yields the following equations:

With respect to the line current,

$$I_L = I_a + I_f, \text{ amperes} \quad (2)$$

The terminal voltage is written,

$$V_t = E_a + I_a R_a = I_f R_f, \text{ volts} \quad (3)$$

Where E_a = counter *e.m.f.* of the motor

I_a = armature current

R_a = armature resistance

I_f = shunt field current

R_f = shunt field resistance

It follows that

$$I_a = \frac{V_t - E_a}{R_a}, \text{ amperes, also} \quad (4)$$

$$I_f = \frac{V_t}{R_f}, \text{ amperes} \quad (5)$$

Similarly in a series motor, fig. 25, the following equations are obtained:

$$I_a = I_L, \text{ amperes} \quad (6)$$

Because here the armature and the field are in series with one another.

The terminal voltage is,

$$V_t = E_a + I_a (R_a + R_s), \text{ volts} \quad (7)$$

Where R_s = series field resistance,

It follows that

$$I_a = \frac{V_t - E_a}{R_a + R_s}, \text{ amperes} \quad (8)$$

and

$$E_a = V_t - I_a (R_a + R_s), \text{ volts} \quad (9)$$

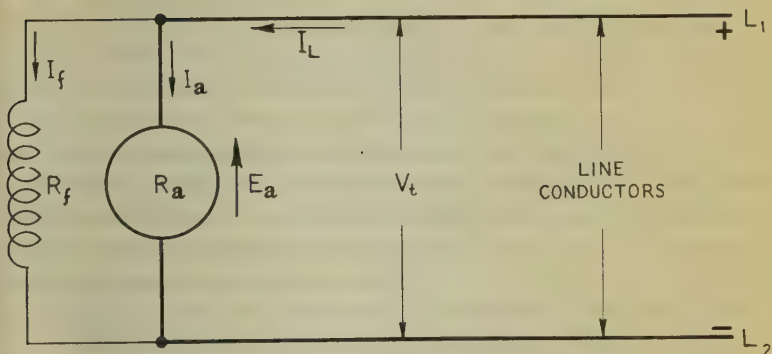


FIG. 24.—Schematic diagram of shunt motor. Letters indicate current, voltage and resistance as indicated in text.

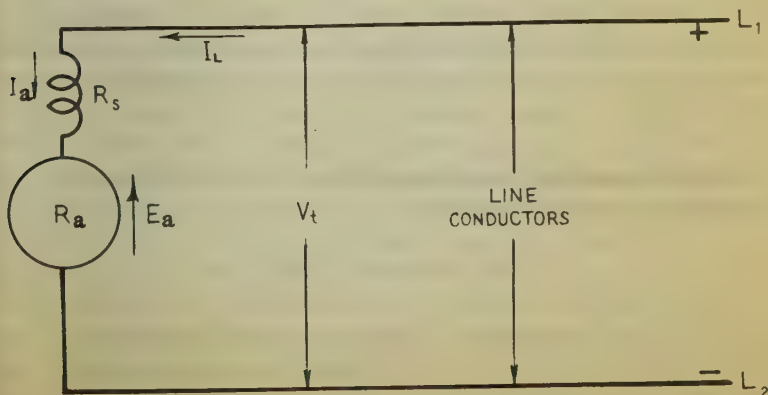


FIG. 25.—Schematic diagram of series motor.

Speed Equation for a Series Motor.—In a series motor, fig. 25, the armature and the field are in series with each other. Neglecting saturation, the torque is proportional to the flux and the armature current. It is also nearly proportional to the square of the current.

The speed of the motor is written:

$$N = K_1 \frac{V_t - I_a (R_a + R_s)}{\phi}, \text{ r.p.m.} \quad (10)$$

At light loads, when the armature current decreases toward zero, the field likewise decreases and the effect is similar to opening the field of a shunt motor, that is, the armature *r.p.m.* increases to higher and higher speeds usually resulting in complete motor destruction. For this reason series motors should always be geared or directly connected and never belted, for if the belt be broken the armature would run away.

It is for the same reason that the field of a shunt motor should never be opened.

The speed characteristics, fig. 14, which is very nearly a rectangular hyperbola, also indicates very clearly the fact that with a series motor the speed is high at light loads and low at high loads.

Speed Equation for a Shunt Motor.—In a shunt motor, the speed in *r.p.m.* is given by:

$$N = K_1 \frac{V_t - I_a R_a}{\phi} \quad (11)$$

With this motor there is no danger of excessive speed. As the motor tends to speed up, the field remaining constant, the current and consequently the torque is decreased, due to the increased counter-electromotive force, and the motor will soon

attain a speed such that the torque just balances the friction and other factors affecting the motion. A typical speed characteristic curve for a shunt motor is given in fig. 15.

Shunt motors may be compounded with a series winding on the field poles. If the series ampere-turns aid the shunt ampere-turns the motor is *cumulatively compounded*. If they oppose the shunt winding they are *differentially compounded*.

The speed and torque characteristics of a cumulative compound motor may approach those of the shunt or series motor as limits depending upon the strength of the two fields.

The differentially compound motor may be adjusted to have a flat speed-load characteristic, but a differential winding tends toward instability and the speed of the shunt motor is ordinarily sufficiently constant for most work.

Direct Current Motors Starting and Reversal of Rotation

General.—In order to prevent damage to a motor when starting, it is necessary to use a variable starting resistance (starting rheostat) in series with the armature. The need for such a starting resistance will become apparent if it be considered that should a motor whose armature is at rest be connected directly to the line, the initial inrush of current would be limited only by the resistance and self-inductance of the armature and series field winding (when used). Since these resistances are very small, this current would reach a value several times the normal full-load current and as a consequence the motor would be severely damaged if not completely burned out.

Calculation of Resistance Steps in a Shunt Motor Starting Rheostat.—The terminal voltage of a shunt motor is given by

$$V_t = E_a + I_a R_a \quad (12)$$

Since the only opposition to the current at the closing of the circuit is the armature resistance R_a , it is obvious that some form of external resistance is required, not only for limiting the instantaneous starting current, but also for protecting the motor itself.

An appreciation of the numerical value of this current will be obtained if equation (12) be solved with respect to I_a , or

$$I_a = \frac{V_t - E_a}{R_a} \quad (13)$$

Thus, for example, in the case of 15 *h.p.*, 220 volt motor in which the armature resistance $R_a = 0.2$ ohm, the instantaneous current inrush through the armature would be

$$I_a = \frac{220 - 0}{0.2} = 1,100 \text{ amperes}$$

Since the normal full load current of such a motor amounts to about 60 amperes, the *need for a current limiting device becomes apparent.*

This current limiting device, is known as the *starting rheostat*, and consists of a number of resistance steps in which a step is cut out each time the current falls to a predetermined value.

The starting resistance is generally so designed, that the motor will start full-load with a starting current not to exceed 150% of full load current.

A resistance necessary to meet these requirements from equation (13) is

$$I_a = \frac{V_t - E_a}{R_a + R_{x1}} \quad (14)$$

Where R_a = armature resistance

R_{x1} = total resistance of starting rheostat

The procedure of calculation will be illustrated by considering the following:

Example.—*It is required to determine both the total rheostat resistance and each successive step of resistance in a starter, fig. 25A, to be used with a 220-volt shunt motor in which $R_a = 0.2$ ohm and full-load current $I_a = 58$ amperes.*

Solution.—Solving for R_{x1} , in equation (14) gives

$$R_{x1} = \frac{V_t - (E_a + I_a R_a)}{I_a} \quad (15)$$

Assuming a starting current of 150% times full-load current, then at zero speed the induced voltage is zero, and

$$R_{x1} = \frac{220 - (0 + 1.5 \times 58 \times 0.2)}{1.5 \times 58} = 2.329 \text{ ohms}$$

If the motor is starting full load, the current will drop to approximately the rated value after it has accelerated its load and the induced voltage

$$E_a = V_t - I_a (R_a + R_x) = 220 - 58 (0.2 + 2.329) = 73.32 \text{ volts}$$

To accelerate the armature further the resistance must be reduced to

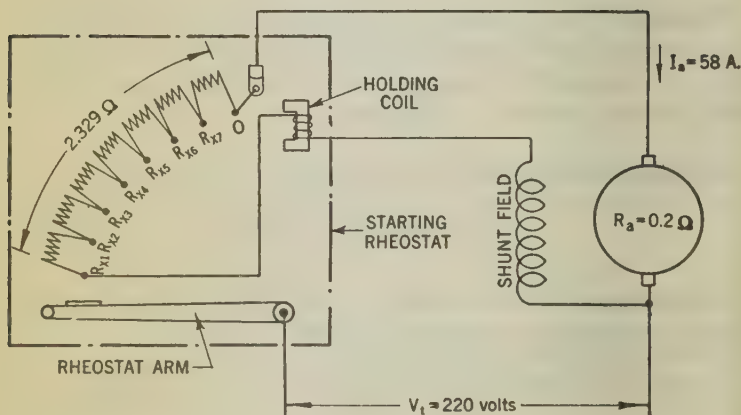
$$R_{x2} = \frac{220 - (73.32 + 1.5 \times 58 \times 0.2)}{1.5 \times 58}$$

$$= \frac{220 - (73.32 + 17.4)}{87} = 1.486 \text{ ohms}$$

The induced voltage

$$E_a = 220 - 58 (0.2 + 1.486) = 122.21 \text{ volts}$$

$$\text{and } R_{x3} = \frac{220 - (122.21 + 17.4)}{87} = 0.924 \text{ ohm}$$



BUTTONS	RESISTANCE	OHMS
Rx1 - Rx2	2.329 - 1.486	0.843
Rx2 - Rx3	1.486 - 0.924	0.562
Rx3 - Rx4	0.924 - 0.549	0.375
Rx4 - Rx5	0.549 - 0.300	0.249
Rx5 - Rx6	0.300 - 0.133	0.167
Rx6 - Rx7	0.133 - 0.0219	0.1111
Rx7 - 0	0.0219 - 0	0.0219

FIG. 25a.—Starting resistance box, and step resistance value for 15 h.p. 220 volt-shunt motor.

The remaining steps are carried out in the above manner until the induced voltage E_a approximately equals the terminal voltage. The ohmic resistance value between the two buttons at the extreme left on our rheostat = $R_{x1} - R_{x2}$, between the next two buttons $R_{x2} - R_{x3}$, etc. Starting rheostats generally have from 7 to 10 buttons.

Reversing of Rotation.—To reverse the direction of rotation in any direct current motor, the connections of the *armature terminals alone*, or the connections of the *field winding* (or field windings) *alone* must be reversed. If both (or all) be reversed, the direction remains unchanged. The foregoing will be apparent from a study of the equation for the torque, which is:

$$T = K\phi I_a \quad (16)$$

A negative torque (which will result in a reversal of direction) will be obtained by changing the polarity of the *current* or the *flux*. If *both* be changed the result will be a positive or unchanged torque, since a negative value multiplied by another negative value will give a positive product.

Direct Current Motor Controllers

General.—Direct current motor controllers are divided into two principal classes depending upon their method of operation, as:

1. Manual controllers, and
2. Magnetic controllers.

In the former the acceleration of the motor armature is performed entirely by manipulation of the rheostat arm (or arms) by hand, whereas in the latter the starter is moved into position by the magnetic action of a coil (or coils) which is usually

energized by the closing of a light auxiliary switch, or switches, usually called starting buttons.

Manual Controllers.—These are supplied in three principal forms termed as: (a) *Face-plate controllers*, (b) *Multi-switch controllers*, and (c) *Drum controllers*.

Face-Plate Controllers.—These are divided into various classifications depending upon their duty, as follows:

1. For starting duty only.
2. For starting and regulating duty and providing the speed increases of from one to four times full speed value by field control only.
3. For starting and regulating duty providing a minimum of 50% speed reduction by armature control only.
4. For starting and regulating duty providing a 50% speed reduction by armature control and 25% increase by field control.

From speed regulation by armature control two classes of service are obtained, that is, constant torque and varying torque.

Constant torque applications, include machine tools, plunger type pumps and similar loads where the horsepower output of the motor decreases directly with the motor speed while the torque remains constant.

Varying torque applications include blowers, centrifugal pumps and similar loads where the torque varies approximately as the square of the motor speed.

Operation of Face Plate Controllers.—With reference to figs. 26 and 27, showing the external view and wiring diagram of a face plate controller of *Class One*, or for *starting duty only*,

the operation is as follows: Connection is made from one of the line wires to a contact arm whose function it is to carry the current over a series of stationary contact buttons provided with graduated resistance stops to the motor winding. When the contact arm is moved towards the right, the first connection serves to put the shunt field circuit directly across the line.

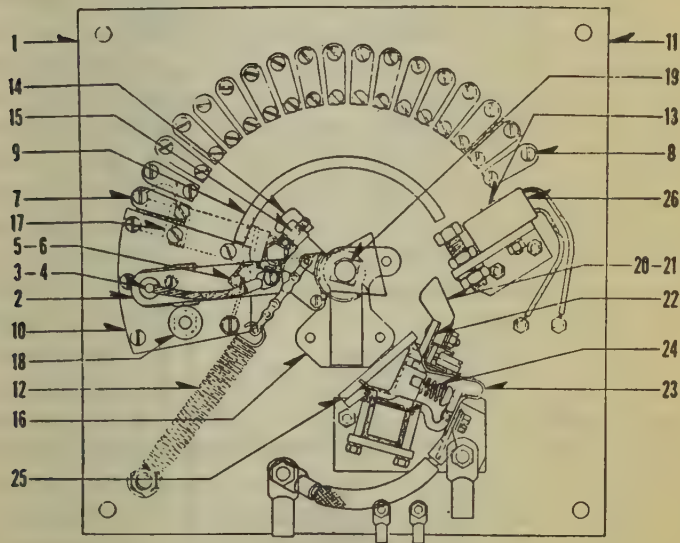


FIG. 26.—External view of typical 25 *h.p.* direct current motor starting rheostat. In the illustration 1, represents face plate; 2, contact arm; 3, contact with shunt-main; 4, contact spring-main; 5, contact without shunt-auxiliary; 6, contact spring-auxiliary; 7, stationary contact; 8, stationary contact stud; 9, stationary contact segment; 10, rider; 11, base; 12, return spring; 13, magnet core; 14, contact; 15, contact screw; 16, bearing bracket; 17, blowout coil; 18, rubber stop; 19, shaft assembly; 20, type A contact finger; 21, finger tip; 22, finger base; 23, finger shunt; 24, finger spring; 25, finger arc barrier; 26, magnet coil.

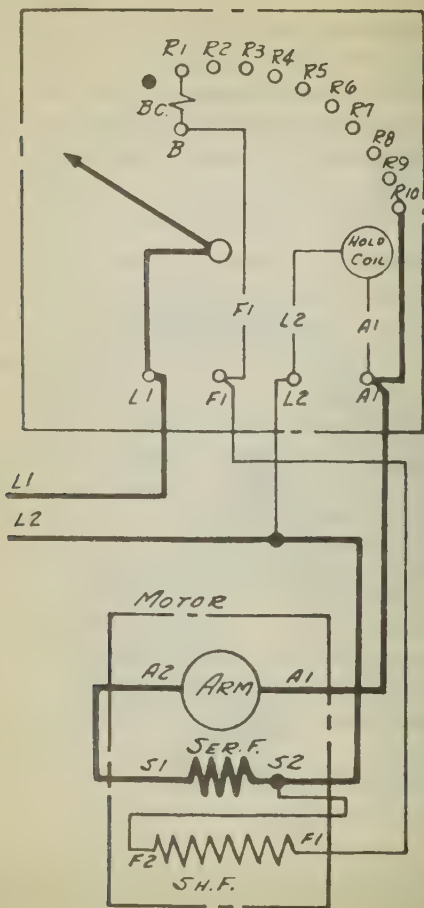


Fig. 27.—Typical wiring diagram showing connection of a compound-wound motor to its face plate starter. For shunt-wound motors the series field coil is omitted. This starter is used for *starting duty only*.

When the contact arm is moved over all the way to the right which is the "running position" it makes contact with a magnet (variously termed holding coil or no-voltage release) whose purpose it is to hold the contact arm in position during normal conditions of the circuit.

If, however, the voltage fails, the magnet coil will be de-energized and the contact arm is carried back to its original position by spring action. This action prevents the motor from the risk of being connected directly across the line when voltage is restored to the line.

Motor face plate controllers of the *Second Class* designed for both starting and speed regulating duty (fig. 28) combine the functions of starting, by means of armature resistance, and speed regulation by means of field circuit resistance.

Thus, the speed regulating rheostats have a compound contact arm, one for starting and one for regulating speed. The starting arm is spring-retained. In starting, the starting arm is moved to the running position (by the regulating arm) where it is held by the low-voltage release magnet while the regulating arm is carried back to the correct point for the desired speed.

Motor face plate controllers of the *Third Class* designed for speed regulation, below normal speed by armature resistance only, are very similar to rheostats of *Class One* with the exception that all the starting buttons or segments must be dimensioned to carry the full load current continuously. In this type of rheostat the no-voltage release is arranged to hold the movable contact arm at any desired point. This is accomplished by equipping the contact arm with a "pawl" and the magnet operates to hold the contact arm in any operation position.

The *Fourth Class* of face plate controller is designed to reduce the speed of the motor 50%, when fully loaded at

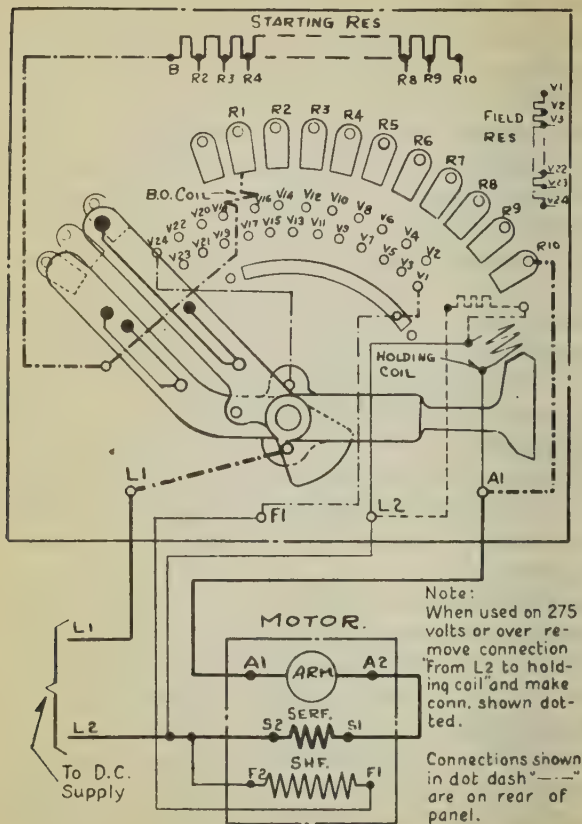


FIG. 28 — Typical wiring diagram showing connection of a compound-wound motor to its face plate starter. For shunt-wound motors the series field coil is omitted. This starter is used for starting and speed regulating duty by field control only.

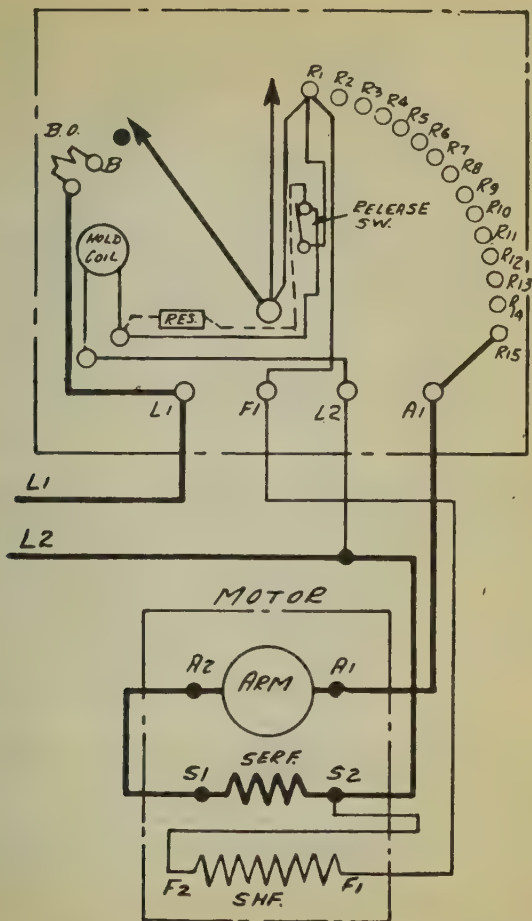


FIG. 29.—Typical wiring diagram showing connection of a compound-wound motor to its face plate starter. For shunt-wound motors the series field coil is omitted. This starter is for speed regulating duty—50% speed reduction by armature control.

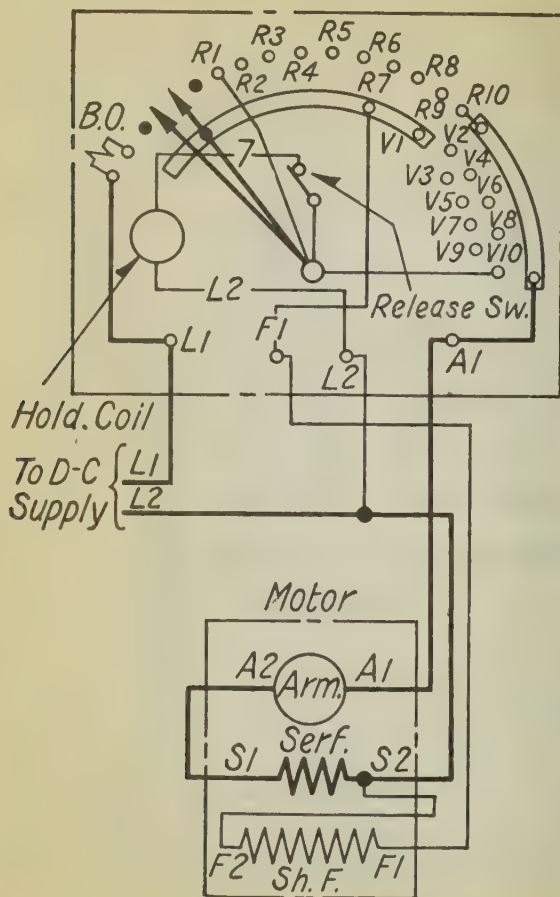


FIG. 30.—Typical wiring diagram, showing connection of a compound-wound motor to its face plate starter. For shunt-wound motors the series field coil is omitted. This starter is used for speed regulating duty—50% speed reduction by armature control and 25% increase by field control.

normal speed, by inserting resistance in the armature circuit, and increase the speed 25% by regulating the resistance in the field circuit. A typical wiring diagram for a controller of this class is shown in fig. 30.

These controllers are designed in two types, one having a small number of field regulating steps, and the other a large number.

Controllers equipped with a relatively small number of buttons (resistance steps) are used for standard constant speed motors, where it is desired to increase the speed by 25% by weakening of the field current.

A large number of buttons (resistance steps) signifies starting rheostats where a wide range of speed is desired by field control regulation.

Multiple-Switch Controllers.—These are designed with a series of switches which must be closed manually in a left-to-right sequence, with a hand-over-hand motion.

This arrangement provides a certain element of safety due to the time element required, as compared to the manual starter, where the operator often gives the controller rough treatment by cutting out resistance too rapidly.

Successive portions of the starting resistance is cut out as each switch is closed. The switches are so mechanically interlocked as to prevent closing in any other sequence than the proper sequence. Each successive switch mechanically locks in the preceding one.

The last switch is locked in by a catch which is held by a low voltage protection magnet. Ratings run to 150 *h.p.* and are especially adaptable to large motor manual starting because of the time element introduced by the hand-over-hand closing

procedure necessary. Multiple switch units are for starting duty only, without dynamic braking and for non-reversing service of either shunt, series or compound wound motors.

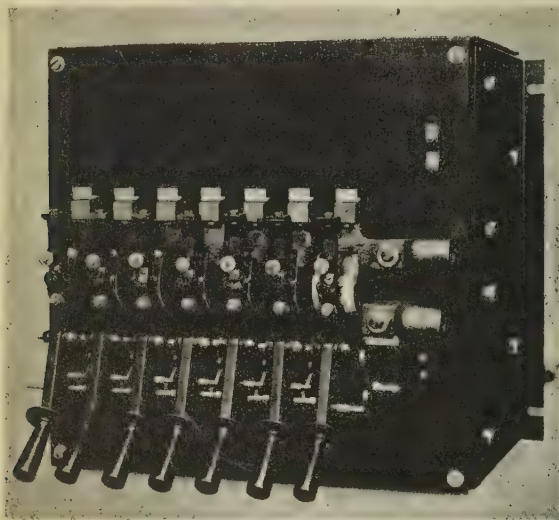


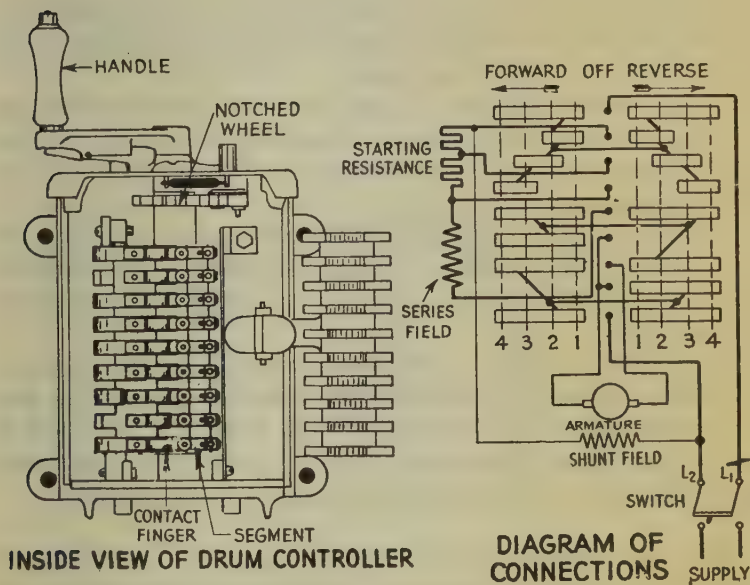
FIG. 31.—Exterior view of typical multiple switch controller.

Drum Controllers.—These are used for starting and control of adjustable speed motors having speed ranges of four to one or less.

Drum controllers are used for control of both alternating current and direct current motors in various services, such as in the machine tool industry, hoisting work, for control of trolley car motors, railroad motors, etc.

When used in connection with direct current motors, drum controllers are available for both reversing and non-reversing service and for armature-starting field regulating.

Operation of Drum Controller.—With reference to figs. 32 and 33, the drum controller consists essentially of a drum cylinder insulated from its central shaft to which the operating handle is attached. To facilitate the operation, copper segments are attached to the drum. These segments are connected to and insulated from one another as shown in the diagram of connections.



FIGS. 32 and 33.—Wiring diagram and inside view of typical drum controller.

A series of stationary fingers are arranged to contact with the segments. These fingers are insulated from one another but inter-connected to the starting resistance and the motor circuit.

The drum assembly has a notched wheel keyed to the central shaft, the function of which is to indicate to the operator when complete contacts are made. With reference to the diagram, when the controller is moved forward one notch, the fingers are in position 1. The current then flows from L_1 through all the series resistance to L_2 and the motor starts rotating. When the handle is moved further, the resistance is gradually being cut out of the armature circuit and inserted in the field circuit. Finally, when the handle is turned to notch 4, all the resistance has been transferred from the armature to the field circuit, and the motor is running at full speed.

Drum control units may be obtained with dynamic breaking resistor, and in some instances, a magnetic contactor. A protective panel can also be provided to obtain overload and low voltage protection.

Drum controllers are generally provided with a reset contact that requires the drum to be returned to the "off" position before the protective panel can be reset after the overload or voltage failure.

Overload protection is usually obtained by instantaneous thermal relays having inverse time characteristics for normal overloads but trip instantaneously on abnormal overloads of about four times normal load or more. Reset can be manual (after returning controller to off) or can be made automatic.

Blow-Out Magnet.—The function of the blow-out magnet as used on drum controllers is to extinguish the electric arc formed as the contacts open, thus preventing the fingers and corresponding contacts from damage. This extinguishing effect is provided by means of a magnetic blow-out coil, which is shown in diagrammatic form in fig. 34.

An asbestos plate is hinged to the core of the blow-out coil and extends the full length of the drum, and from it arc barriers project down between the fingers.

The current through the blow-out coil sets up a strong magnetic flux which passes across the contacts. As the contact opens, the current forms an electric arc, which is deflected upward or downward depending upon the direction of the current in the arc. The arc, in deflecting will strike the asbestos barrier above or below the finger and will draw out to such an extent that it will be dissipated.

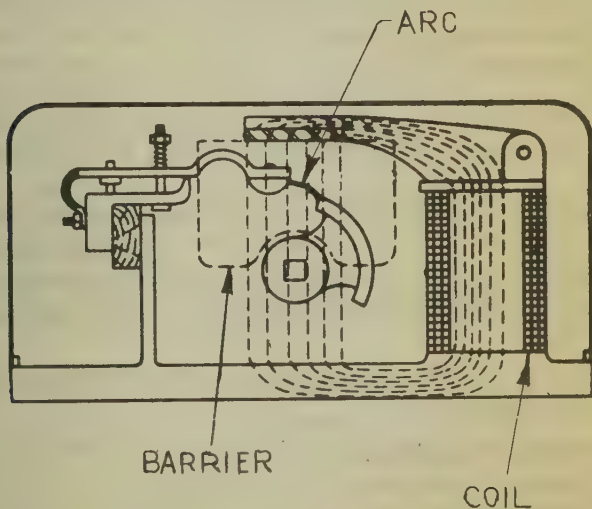


FIG. 34.—Illustrating cross-section of typical drum controller and action of blow-out coil.

In other controllers, the magnet blow-out coil is of a long narrow shape surrounding the piece of the pole piece and carried just over the line of the contact fingers.

In all cases, however, the winding of the blow-out coil is connected in series with the armature of the motor, so that whatever current passes through the blow-out coil provides the necessary magnetic flux which is, therefore, approximately proportional to the amount of current supplied to the motor. The blow-out coil is made of copper wire or copper bars the size and turns being determined by the motor current in each instance.

Magnetic Controllers.—Magnetic controllers or starters are classified according to their control features, as:

1. Semi-automatic, and
2. Automatic.

Semi-automatic control requires manual actuation such as an operator pushing a button for start or stop, inch or forward or reverse.

An automatic starter on the other hand functions without human actuation and exists wholly due to special conditions and design features; an example may be had in a motor operated float switch, a pressure operated switch, a time limit switch, etc.

Magnetic controllers are again classified according to their accelerating features, as:

3. Definite time limit,
4. Current limit, and
5. Counter-*e.m.f.*

Definite Time Limit Starters.—These are simple in construction, accelerate the motor with low current peaks, use less power during acceleration and always accelerates the motor in the same time regardless of variations in load.

Definite time delay may be obtained in one of several methods. A "pawl" and "ratchet" mechanism attached to the gears of timing device permit the operating solenoid to operate at a predetermined moment. An escapement mechanism is another way of obtaining time delay.

Inductive time-limit acceleration makes use of the inductive time-lag effect of the decay of current in a heavily inductive circuit. Sometimes called magnetic timing, the inductive time-limit contactors may be of the normally open hold-out type or of the normally closed type.

In a similar manner, capacitor time-limit acceleration makes use of the constant discharge time of a capacitor in the sequence operation of the accelerating contactors.

Standard magnetic accelerating equipment is available in ratings up to 150 *h.p.* for reversing or non-reversing service, with or without dynamic braking.

Braking can be obtained by several methods. Dynamic braking makes use of a discharge resistor placed across the motor terminals after the main contactor has disconnected the motor from the line.

Plugging is obtained by reversing the armature connections while running and accomplishes a very rapid reversal of the armature.

Magnetic brakes are used to obtain quick, accurate stopping, and to hold the load after stopping. Most brakes are electrically released and spring set, so that braking will be obtained even though an electrical failure should occur.

In addition to overload and low voltage protection, very often other types of protection are required. Over-speed or under-speed protection can be obtained by means of centrifugal governors or tachometers. Control functions may thus be initiated at any predetermined speed value to accomplish any desired reaction.

Field-failure protection is usually provided to disconnect the motor from the line in the event of an open shunt field in either shunt or compound wound motors. A relay coil is connected in series with the shunt field to give the signal on open field condition.

Field protective relays are often used to insert resistance in series with the shunt field when the motor is not in operation, thus preventing overheating of the shunt field while the motor is at standstill.

When shunt field circuits must be opened, field discharge resistances should be provided to limit induced voltage to a value that will not damage field winding insulation when the field circuit is open.

Current Limit Starters.—Acceleration by current limit depends wholly upon values of the armature current, and contactor operation may be regulated to any predetermined value. For example, when the start button is pressed and the main line contactor closes with all the starting resistance in the circuit, a certain value of inrush current (say 150%) is encountered, which finally decreases to some value (say 115%). At 115%, the first accelerating contactor closes shorting out part of the resistance, and the inrush current immediately increases only to decrease again as motor speed picks up. This increases the counter-*e.m.f.* and the second accelerating contactor closes when the current decreases to the preset value, etc.

Current limit acceleration is entirely dependent upon load. Light loads will accelerate rapidly and heavier loads will require a longer time to accelerate. For this reason current limit starting is not so satisfactory for varying loads.

It is entirely possible that under heavy load starting, if the speed could not pick up to the point where the current could be

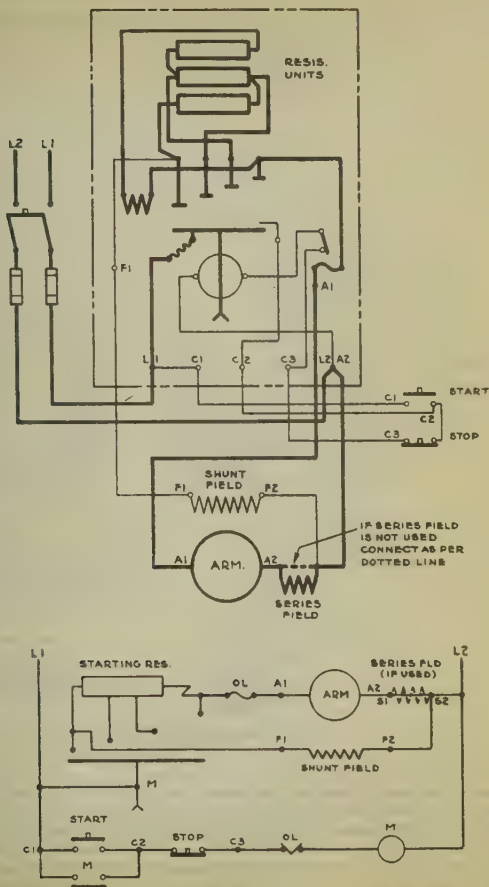


FIG. 35.—Connection diagram showing a typical direct current time limit acceleration starter. The principles of operation consists mainly in cutting out steps of a resistance by means of a timing device.

reduced to actuate the succeeding accelerating contactor, the motor would operate at that point with starting resistance still in the armature circuit. Current limit starting is most desirable for motors driving high inertia loads.

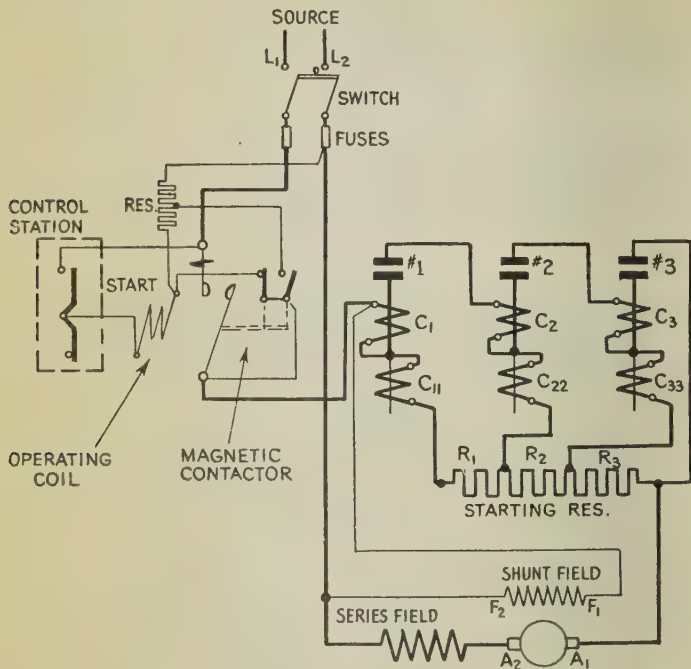


FIG. 36.—Connection diagram illustrating a current limit acceleration starter. This system of control utilizes separately mounted contactors to control each step of acceleration. When the starting button is closed energizing the operating coil the magnetic contactor closes. The starting current flows from L_2 through the series field, armature, starting resistance, contactor coils C_1 and C_{11} to L_1 . The shunt field is connected directly across the line. After the current through contactor #1 has reached the contactors setting value, this contactor closes its contact, shunting out coils C_1 , C_{11} and R_1 . This operation provides a current path through C_{22} , C_2 via contactor #1 and its coil C_1 . After the current through contactor #2 has reached the contactors setting value, this contactor closes, and so the process is repeated until all the contactors are being closed, at which time the motor is connected directly across the line.

Counter e.m.f. Starters.—Counter *e.m.f.* acceleration uses a form of current limit acceleration. The accelerating contactors close in succession as the voltage across the armature increases until the motor is finally brought to full speed with the closing of the last accelerating contactor. This type of control is usually limited to motors rated up to 5 *h.p.*

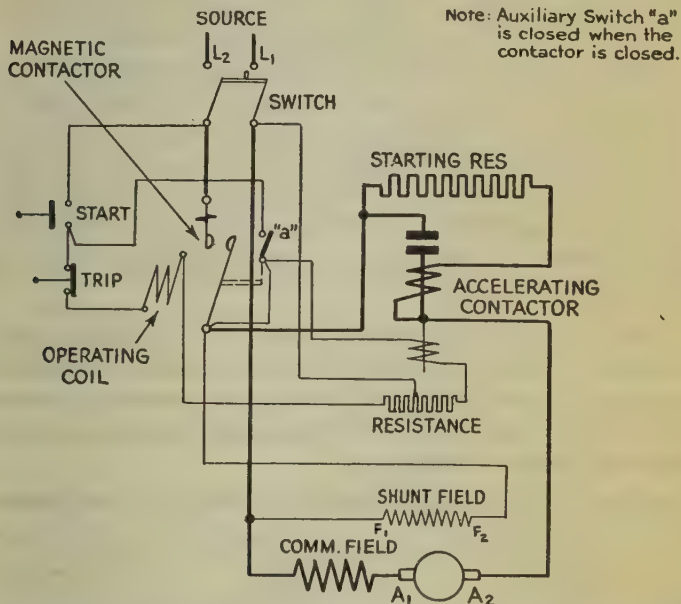


FIG. 37.—Connection diagram illustrating typical counter *e.m.f.* motor starter. With reference to the diagram, the starter consists principally of two contactors; the magnetic contactor and the accelerating contactor. The magnetic contactor is used to close the line supply to the motor. Its coil is connected directly across the line and is closed or operated by a starting push button or toggle switch. When the starting button is pressed, the operating coil is energized through a resistance closing the magnetic contactor. After the finger has been removed from the starting button the lower section of the accelerating contactor is placed in series with the magnetic contactor operating coil. This reduces the power required to hold the magnetic contactor closed and the magnetizing action of the lower accelerating contactor coil aids the upper section of the coil closing this contactor when the armature voltage has reached a predetermined value. The motor is disconnected from its source by means of operation of the trip button which de-energizes the operating coil causing the magnetic contactor to open.

Advantages of Magnetic Controllers.—Magnetic controllers are generally used because of the advantage over other forms in that the acceleration (time element) required for the motor starting, is removed from the physical effort of the operator.

With the phase plate type of controller, for example, the operator may accelerate the motor too rapidly, resulting in the motor taking excessive current. This usually results in burnt out fuses, resistances, or opening of circuit breakers.

With magnetic controllers the starting resistance may be cut out at the maximum safe rate by means of magnetically operated switches. The operator's duty is to push a button, the magnetic switch starts the motor and accelerates it by cutting out the starting resistance. When stopping or reversing the motor, the pressing of the button marked "stop" or "reversing" opens or closes the correct contactor or contactors to perform the desired operation.

Magnetic starting is especially adapted to frequent starting operations; or when the motor is located at some distance from the operator, when space does not permit mounting a manual controller near the operator, or when large motors require commutation of heavy currents.

Common Field of Applications for Direct Current Motors.

Series	Shunt	Compound
Bailing presses	Agitators	Balers
Bridges	Blowers	Bending rolls
Cranes	Conveyors	Bulldozers
Car retarders and pulleys	Fans	Metal drawers
Coke oven machinery	Line shafts	Punch presses
Hoists	Printing presses	Shears
Hydraulic cages	Pumps	
Lorry cars	Mixers	
Rotary car dumpers	Most machine tools	
Yard locomotives	Most wood work mach.	

Typical Connection Diagrams

The following pages contain a number of representative connection diagrams of direct current motors. Due to the fact that various manufacturers of equipment use different wiring symbols and control apparatus, great care should be observed when connecting electrical apparatus. The connection diagrams furnished by the manufacturers of equipment should be followed in each individual case.

Care should also be taken when wiring motors and control into electric circuits, to see that conductors of the proper sizes are used, that standard safety precautions are taken, and that the apparatus is adequately protected against abnormal conditions, such as short circuits.

The *National Electrical Code*, modified by local ordinances, should serve as a guide, wherever electrical equipment is installed and operated.

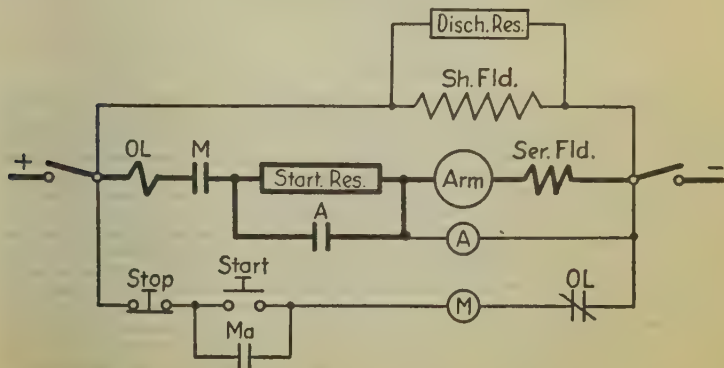


FIG. 38.—Basic requirements of a non-reversing D.C. starter in its simplest form. When the start push button is depressed, line contactor *M* closes, energizing the motor armature through the starting resistance. As the motor comes up to speed the counter-voltage and the voltage across motor armature and series field, increases. At a predetermined value the accelerating contactor *A* closes, shorting out the starting resistance.

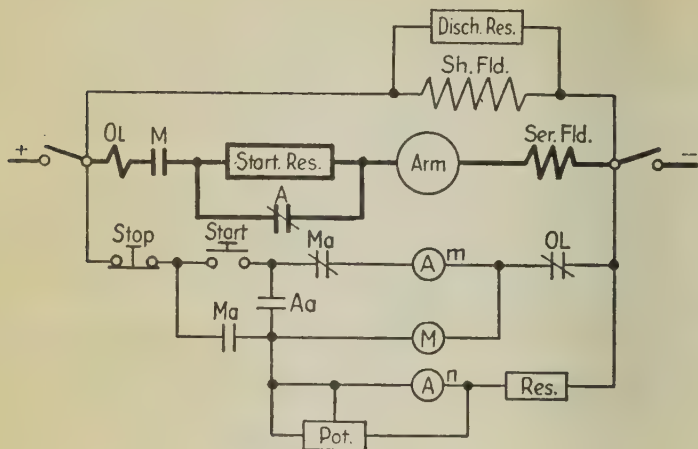


FIG. 39.—Typical non-reversing, constant speed, definite-time starter. The accelerating contactor is equipped with a time-delay mechanism. This contactor *A* is of the magnetic-flux-decay type. It is spring closed, equipped with two coils, and has a magnetic circuit that retains enough magnetism to hold the contactor armature closed and the contact open indefinitely. Main coil A_m has sufficient pull to pick up the armature and produce permanent magnetization. Neutralizing coil A_n is connected for polarity opposite to the main coil. It is not strong enough to affect the pick-up or holding ability of the main coil but, when the latter is de-energized, the neutralizing coil will buck the residual magnetism so that the contactor armature is released by the spring and the contacts close. By adjusting the potentiometer the voltage impressed on this coil and hence the time required for the contactor to drop out, can be varied. When the start button is depressed, accelerating contactor coil A_m is energized, causing contact *A* to open and auxiliary contact A_a to close. Contact A_a energizes line contactor *M*, and normally open auxiliary contacts M_a establish a holding circuit. Neutralizing coil A_n is also energized. Opening of contact M_a de-energizes coil A_m , and contactor *A* starts timing. At the set time the main normally closed contacts on *A* close, shorting out the starting resistance and putting the motor across the line.

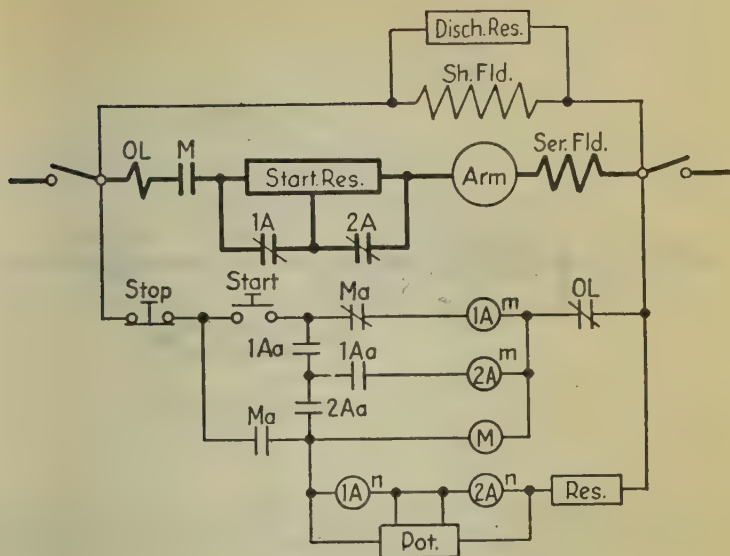


FIG. 40.—The same kind of a starter as in fig. 39, but designed for use with a motor of larger horsepower. This starter provides two steps of definite time starting. The operation is essentially the same as in fig. 39, but the first accelerating contactor 1A does not short out all the starting resistance. It also starts 2A timing, which finally shorts out the remaining resistance. The normally open auxiliary contacts on the accelerating contactors in figs. 39 and 40, are arranged so that it is necessary for the accelerators to pick up before the line contactor can be energized. This is a safety interlocking scheme that prevents starting the motor across the line, if the accelerating contactors are not functioning properly.

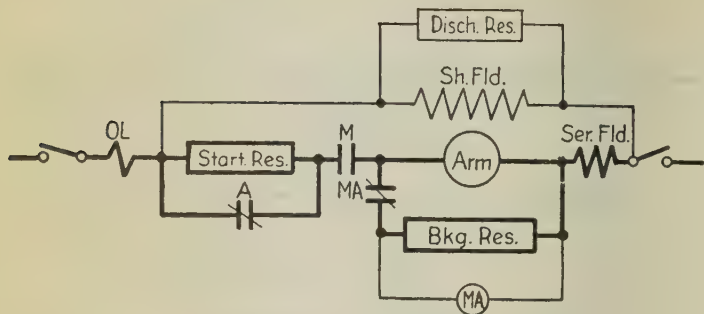


FIG. 41. —One way of producing dynamic braking. Control circuits have been omitted, since they are a duplicate of those shown in figs. 39 and 40. Line contactor *M* has two poles, one normally open and the other normally closed. Both poles are equipped with an operating coil and are on the same armature, which is hinged between the contacts. In starting, when line contactor *M* closes normally closed contact *MA* opens. When the stop button is depressed the line contactor drops out and contacts *MA* close. The motor, now acting as a generator, is connected to the braking resistor and coil *MA* is energized by the resultant voltage. It causes *MA* to seal in tightly, establishing good contact pressure and preventing this contact from bouncing open.

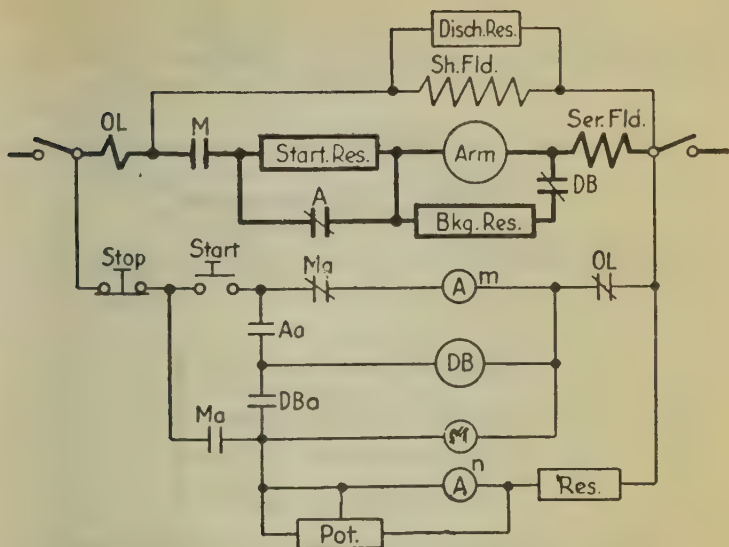


FIG. 42.—In the more modern types of controllers, a separate spring closed contactor is used for dynamic braking. Operating is similar to that described for fig. 39, except that the energizing of coil A_m and the picking up of accelerating contactor A closing contact A_a energizes dynamic braking contactor DB which in turn energizes line contactor M through its auxiliary contact DB_a . This arrangement not only insures that the dynamic braking contactor is open, but also that it is open before the line contactor can close. In order to obtain accurate inching, such as is required for most machine tool drives, the motor must respond instantly to the operation of the push button. In the scheme shown above, the closing of the line contactor is delayed until accelerating contactor and the dynamic braking contactor pick up.

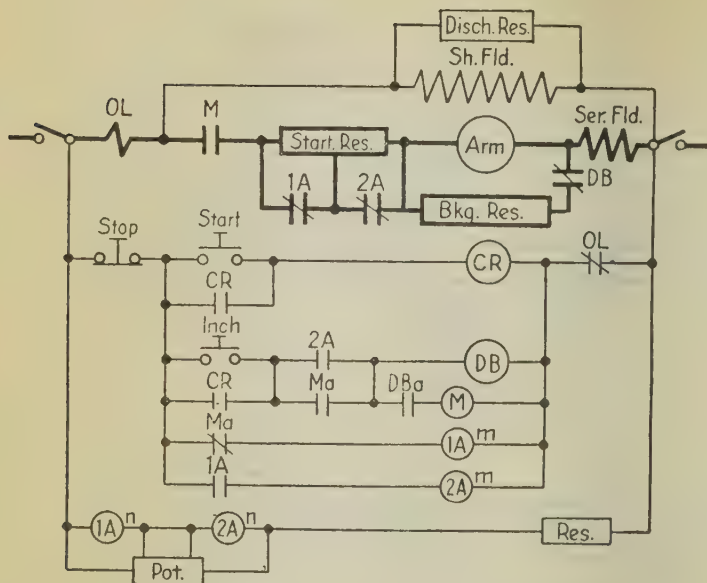


FIG. 43.—Arrangement to secure quicker response of motor, for more accurate inching. Accelerating contactors 1A and 2A are energized in the off position. Hence when the start button is depressed, the dynamic braking contactor picks up immediately and its auxiliary contact DB_a picks up M line contactor.

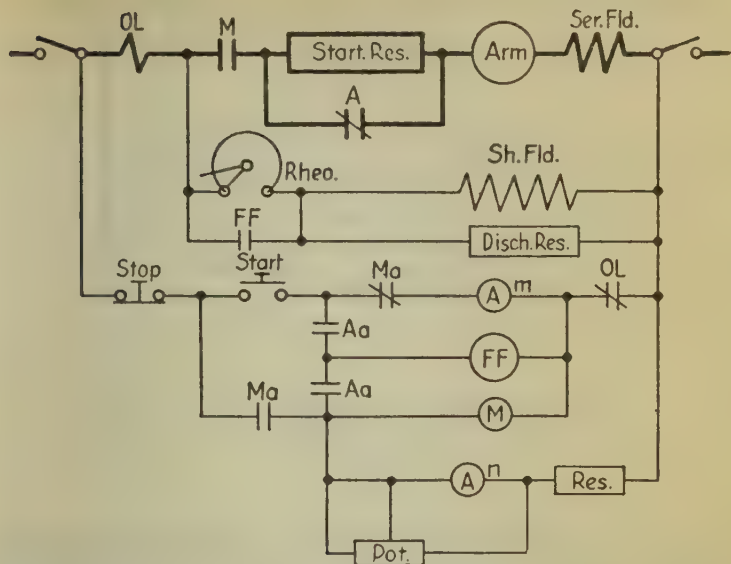


FIG. 44.—One method of connecting full field relay, used with adjustable speed motors having a speed range in excess of 2 to 1. Coil *FF* is energized by the closing of the normally open auxiliary contact *A_a* and remains closed until the last accelerating contactor drops out. Contacts of the full field relay *FF* are connected to short out the field rheostat thereby applying maximum field strength to the motor during the starting period.

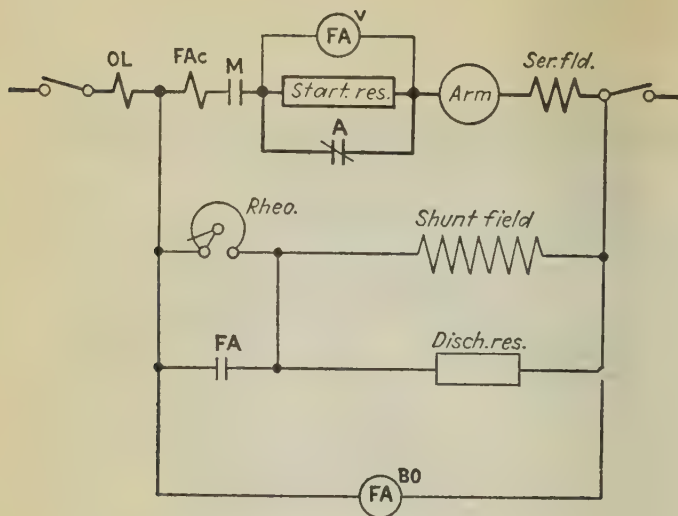


FIG. 45.—Another method of applying the full-field relay. This arrangement insures full field on starting, and provides for limiting the armature current when the motor is accelerating from the full field speed to the speed set by the rheostat. Field accelerating relay *FA* is equipped with two coils, one a voltage coil connected across the starting resistor, the other a current coil connected in series with the motor armature. See fig. 39 for the remainder of the circuit. When line contactor *M* closes the voltage drop across the starting resistor is practically line voltage, and relay *FA*, is picked up quickly. When accelerating contactor *A* closes, voltage coil *FA_v* is shorted, but closing of *A* produces a second current peak, and current coil *FA_c* holds relay *FA* closed. As motor approaches full field speed, this current decays and allows the *FA* contacts to open, weakening the motor field. When the motor attempts to accelerate the line current again increases. If it exceeds the pick-up value of coil *FA_c* the relay will close its contacts, arresting acceleration and causing a decay of line current, which again causes *FA* to drop out. High inductance of the motor field, plus inertia of the motor and drive prevent rapid changes in speed. Hence the motor will not reduce its speed, but the increased field current will reduce the armature current and cause *FA* to drop out. The fluttering action will continue until the motor reaches the speed set by the rheostat. Setting of the *FA* relay current coil determines the maximum current drawn during this part of the accelerating period. Since relay *FA* must handle the highly inductive field circuit, a good blowout arrangement is necessary. Hence the relay is usually equipped with a shunt blowout coil, *FABO*.

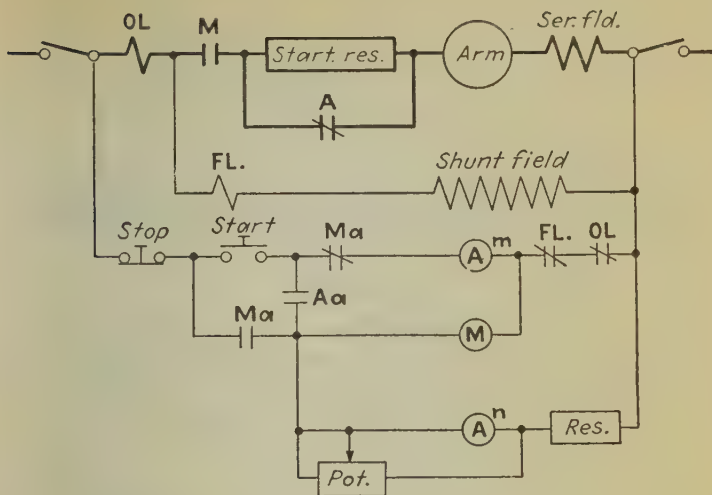


FIG. 46.—Connections of field loss relay, to prevent excessive speed if the shunt field be de-energized while voltage remains on the armature. It usually consists of a current relay in series with the motor shunt field and is adjusted to pick up on full-field current and remain closed at any current within the operating range of the motor field current. Contacts of relay *FL* are connected in series with the overload relay contacts so that the opening of its contacts will de-energize the control by opening the line contactor. This type of field loss protection does not protect against the possibility of a short circuit across a part of the field, say across the one field coil. This would cause the motor speed to rise considerably but the current in the field circuit would also rise. Consequently, the series current relay would not respond.

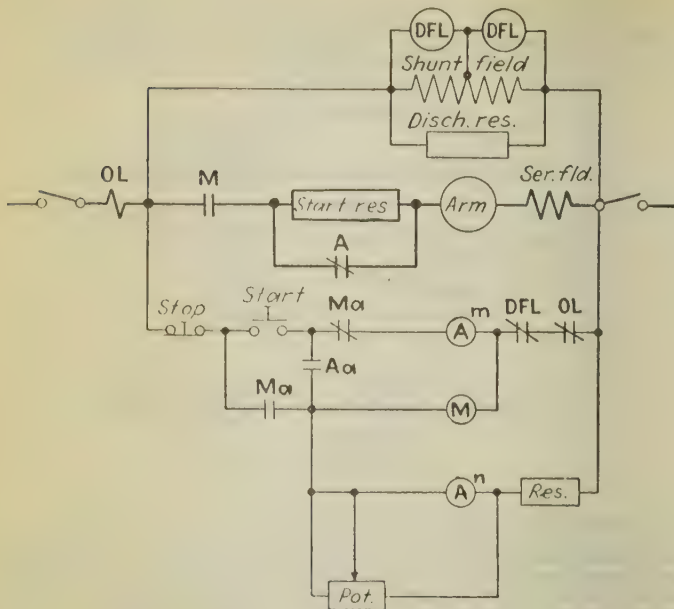


FIG. 47 Application of differential field loss protection. The differential field loss relay *DFL* is equipped with two voltage coils connected to buck each other. Each is connected across one half of the field winding. Normally the voltage across each coil is the same, hence the relay stays in the out position with its normally closed contacts closed. Shorting out of one field coil or other failure causing an unbalance of these voltages causes the relay to pick up, opening its contacts and dropping out the line contactor, de-energizing the motor.

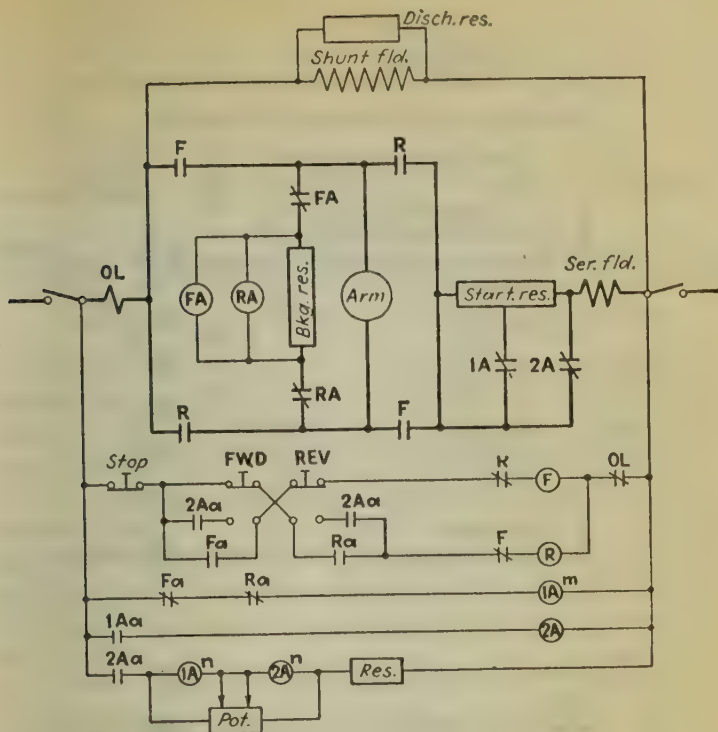


FIG. 48.—One form of reversing dynamic braking control, consisting of multi-pole contactors having two poles normally open and one pole normally closed. Acceleration contactors 1A and 2A are energized in the off position, as in fig. 43. Depressing the forward button energizes forward contactor F, closing the two normally closed auxiliary contact F_a, and opening the normally closed contact FA. Opening of normally closed auxiliary contact F_a starts the timing cycle of the accelerating contactors. Closing of the normally open auxiliary contact F_a establishes a holding circuit. When the stop or reverse button is depressed, contactor F drops out, closing normally closed contact FA and setting up a dynamic braking circuit through the braking resistors, which energizes coils FA and RA. These coils hold the normally closed contact closed, and the normally open contacts open until the braking current drops to a low value. This action prevents bouncing of the back contacts and plugging the motor, because if the reverse button were depressed during the braking period, contactor coil R would not have sufficient strength to overcome the pull of the RA coil until the motor had almost stopped.

CHAPTER 8

The Synchronous Motor

General.—By definition a synchronous motor is a motor which is in unison or in step with the phase of the alternating current which operates it. This condition is only approximated in practice as there is always a slight phase difference.

Any single or polyphase alternator will operate as a synchronous motor when supplied with current at the same potential, frequency and wave shape, as it produces as an alternator, the essential condition in the case of an alternator being that it be speeded up to synchronism before being put in the circuit.

Construction.—In construction, synchronous motors are almost identical with the corresponding alternator, and consist essentially of two elements:

1. Stator (Armature) and
2. Rotor (Field).

A synchronous motor may have either a revolving armature or a revolving field, although most synchronous motors are of the revolving-field type. The stationary armature is attached to the stator frame, while the field magnets are attached to a frame which revolves with the shaft.

The field coils are excited by direct currents either from a small direct current generator (usually mounted on the same shaft as the motor) called an exciter, or from some other direct current source.

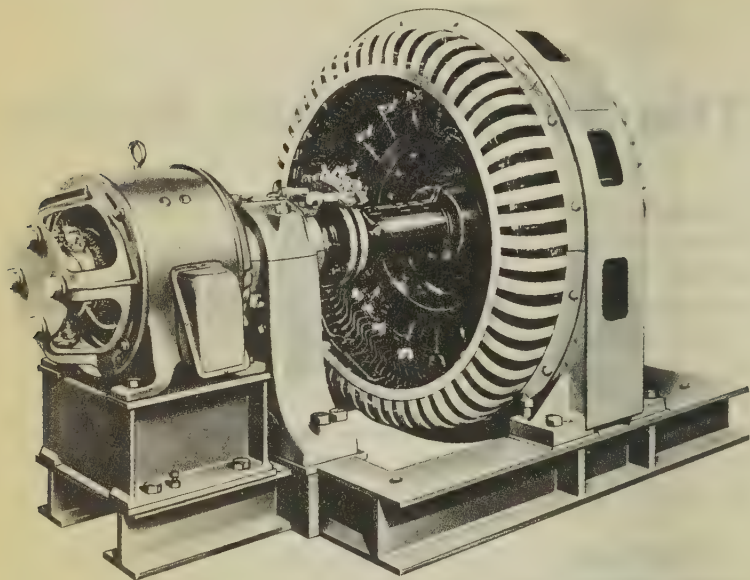


FIG. 1. —Synchronous motor with directly connected exciter. (Courtesy Allis-Chalmers Manufacturing Co.)

Principles of Operation.—When a balanced polyphase alternating current is supplied to the armature of a synchronous motor, it produces a rotating magnetic field which rotates in a synchronism with that of the supply current. It is this rotating magnetic field acting on the damper or amortisseur squirrel cage winding which produces a starting torque causing the rotor to rotate.

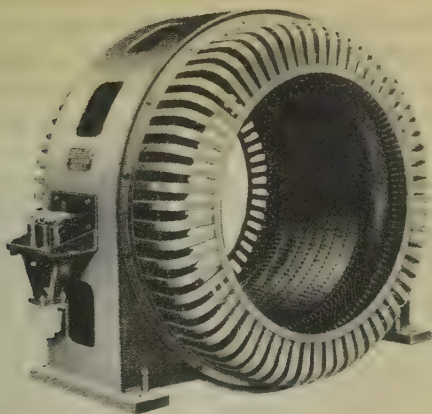


FIG. 2. --Stator of a typical synchronous motor equipped with pot-heat terminal box. (Courtesy Allis-Chalmers Manufacturing Co.)

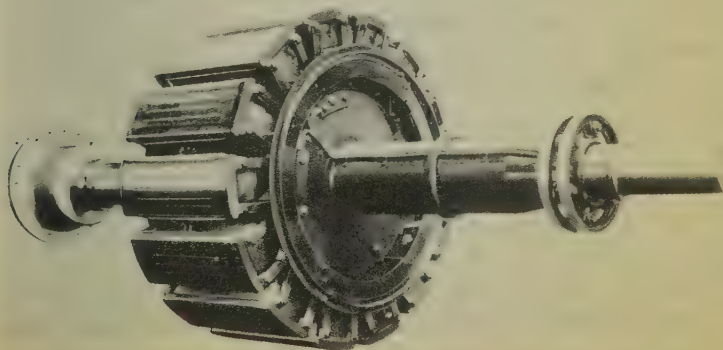


FIG. 3. --Showing rotor construction for typical synchronous motor. (Courtesy Allis-Chalmers Manufacturing Co.)

Due to the fact that the motor starts as a squirrel cage motor, the speed will be slightly less than synchronous.

A direct current is supplied to the rotor winding producing alternate North and South poles which "lock into" position with the rotating field in the armature and the rotor rotates in step with that of the supply current.

It may easily be visualized, however, that while this locking action is powerful if the field system is already up to synchronous speed when the armature current is flowing, there can be no torque when the field poles (assumed to constitute the rotor) are originally stationary, because under this condition the armature poles as they sweep across the field poles will tend to pull the latter first in one direction then in another, and as a result the starting torque is zero. Thus the synchronous motor is not inherently a self-starting machine, but must of necessity be equipped with some form of auxiliary starting device, such as a squirrel cage winding, which will be described in a latter part of this chapter.

A better understanding of the operating principles of the synchronous motor may be had if the diagrams in figs. 5 to 16 be examined. These series of diagrams represent twelve conditions occurring at regular intervals throughout a cycle.

The magnetic field is set up by the alternating current in the windings. Thus, for example, when the current rises in the first phase, a magnetic field is produced only by the first winding. As the current decreases in this and increases in the second, the magnetic field shifts along a little until it is all produced by the second winding. When the third winding has a maximum current the field has shifted a little more. The windings are so distributed that this shifting is uniform and continuous throughout.

The thickness of the lines in these series of diagrams are proportional to the current flowing in the winding, that is, the

thicker the lines, the larger the current. It should be observed that no lines indicates an absence of current in the conductor. The arrows in the diagrams indicate the direction of the currents. Also when one cycle is being completed, another is started. In one cycle the magnetic field rotates from one pole to the next one of similar polarity.

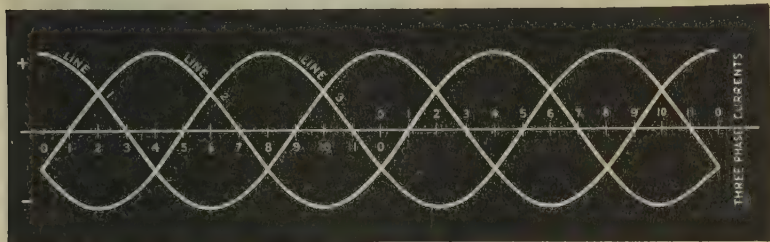
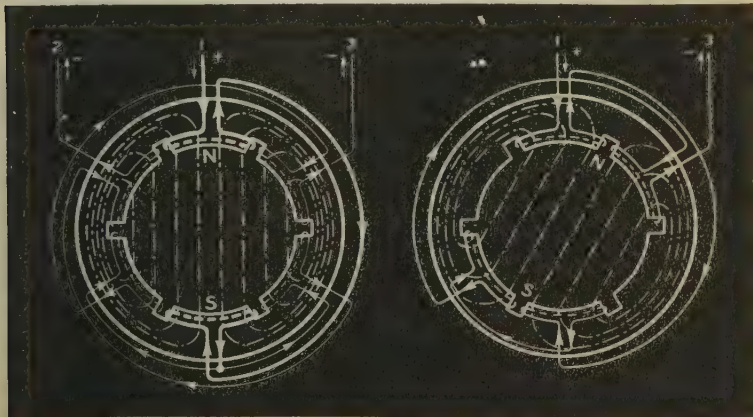
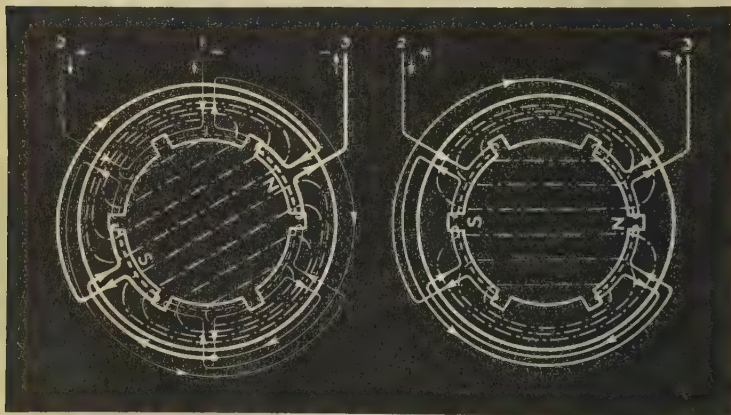


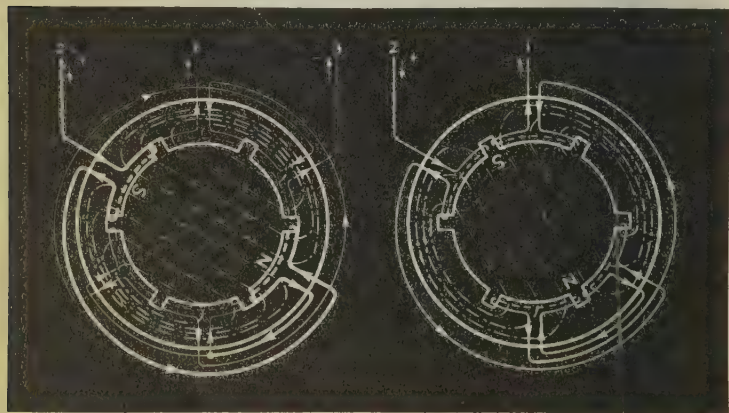
FIG. 4.—Sinusoidal diagram showing current form of a three phase synchronous machine. Diagram covers two complete cycles. Diagrams 5 to 16 illustrates the condition in the armature at the instant indicated by the corresponding number on this curve. The action of the magnetic field is smooth and regular as is the rise and fall of current flowing in the conductors.



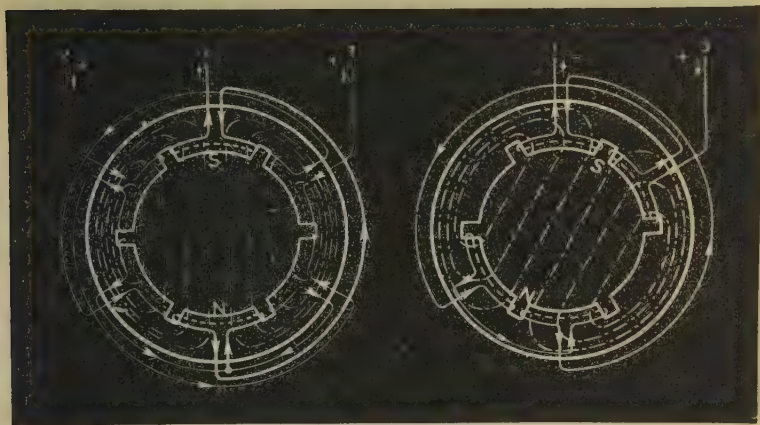
FIGS. 5 and 6.—This and the following series of diagrams show the electric and magnetic conditions in a two pole, three phase motor at the end of twelve equal parts of a cycle. Thus in fig. 5, it will be observed that the current entering the motor on line (1) divides equally and leaves the motor on line (2) and (3). With respect to fig. 6, it will be observed that the current in line (2) is zero, and that flowing in at line (1) leaves at line (3) that is, the magnetic field rotates in a clockwise direction.



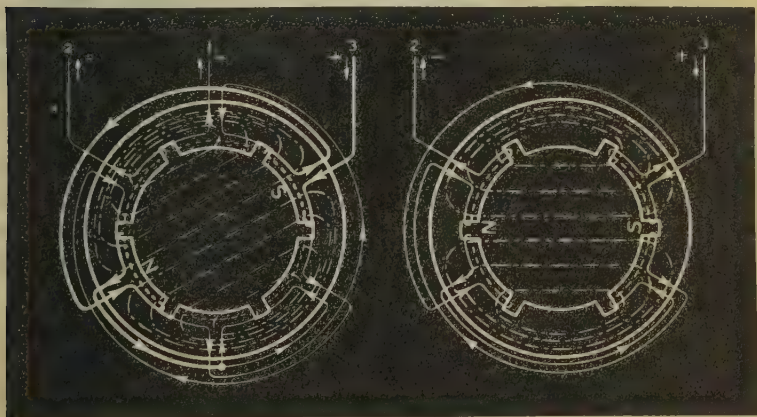
FIGS. 7 and 8.—In diagram fig. 7, the current in line (1) is small and joining that from line (2) which flows out in line (3) which now carries a maximum of negative current. This and the following diagrams show how the magnetic field continues to rotate throughout the remainder of the cycle.



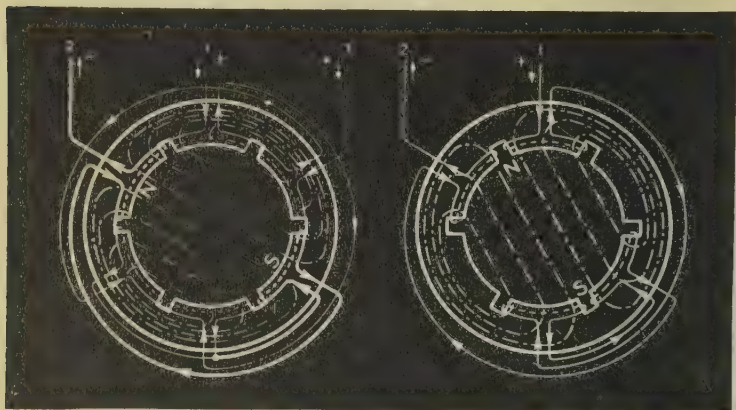
FIGS. 9 and 10.—Illustrating how the magnetic field rotates throughout the cycle.



FIGS. 11 and 12.—Showing the continuous rotation of the magnetic field throughout the cycle in a two-pole three-phase motor.



FIGS. 13 and 14.—Showing the continuous rotation of the magnetic field throughout the cycle in the two-pole, three-phase motor.



FIGS. 15 and 16.—Showing the continuous rotation of the magnetic field throughout the cycle in a two-pole, three-phase motor. The succeeding events with respect to the electrical and magnetic conditions will simply be a repetition of the previously illustrated diagrams.

Excitation.—In the case of a synchronous motor pulling a constant load, a variation in field current is followed by a variation in the stator current giving the well known V-curve pattern shown in fig. 17.

For a given load (with a given motor) there is a single value of field current that will give unity power factor at the motor terminals. Increasing or decreasing the field current from this value will give a power factor less than unity—increasing the field current will give “leading” power factor, decreasing the field current will give “lagging” power factor.

Stated another way, for a given load with constant voltage, if the field current is changed either way from the unity power factor value, “reactive” current will be produced causing the line current to increase as shown in the V-curves. This reactive current will be “leading” if the field excitation is increased or “lagging” if decreased.

Field excitation for the synchronous motor is secured either from an individual induction-motor-driven exciter set, a direct-connected or belted exciter, or a constant D.C. voltage supply such as a station bus. Standard excitation voltage is 125 volts or 250 volts, but the motor field winding is designed for an excitation voltage approximately 10% below this, to allow for voltage drop in the line.

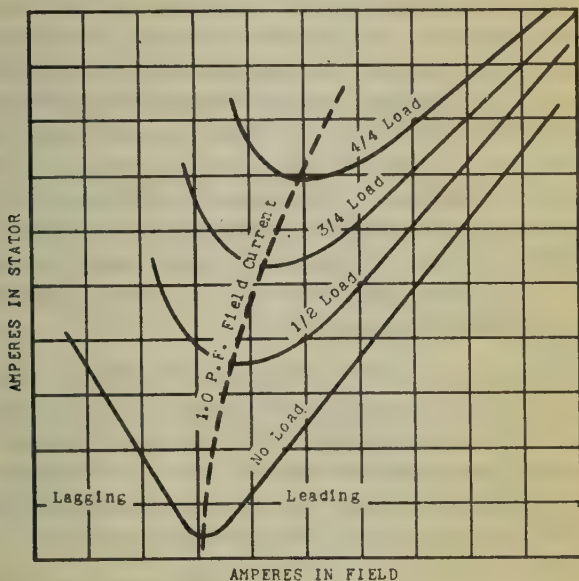


FIG. 17.—Showing typical V-pattern characteristics of a synchronous motor.

In operation of the motor, the field current is usually set at the value of D.C. excitation amperes stamped on the motor nameplate, and kept at this value at all loads. Maintaining

full load nameplate excitation on the motor field maintains the full pull out torque of the motor, and at the same time gives the maximum amount of reactive *kva.* for power factor correction.

If the motor is to be run for long periods of time at considerably reduced load, it may be desirable, in the interest of higher efficiency, to reduce the field current to a value below the nameplate marking that will give nameplate power factor for the actual reduced load point of operation.

For a unity power factor motor operating at part load, the field current is adjusted until the stator current, as read on the A.C. ammeter, is minimum, as illustrated by the V-curves of fig. 17. At minimum stator current, the motor is operating at unity power factor. If then; this field current value is held constant, reference to fig. 18 will show the amount of leading *kva.* supplied to the line. Note that at full load the field excitation is sufficient to operate the motor at unity power factor supplying no *rkva.* However, at half load, it supplies about 22% of the numerical value of the motor's horse-power rating expressed in leading reactive *kva.*

For a leading power factor motor operating at part load, the field current is first adjusted for minimum stator current, or unity power factor, and the minimum line current noted. The field current is then increased so that the stator current rises along the V-curve to the value required for the desired leading power factor as determined by the following formula:

$$\text{Stator current for desired } p.f. = \frac{\text{minimum stator current}}{\text{desired } p.f.}$$

Thus, if the minimum stator current reading is 100 *amp.* and desired leading power factor is 0.8, the field current should be increased until the stator current is $100 \div 0.8 = 125 \text{ amps.}$

The necessary field current adjustment is secured by the exciter field rheostat where individual exciter set, direct-connected or belted, is used; or by a motor field or "series" rheostat where bus excitation is used. The field current should not exceed the rated D.C. excitation amperes.

It should be remembered, however, that when field current is *reduced*, the motor pull-out torque will be *reduced* in proportion and the motor will, therefore, pull out of step more easily.

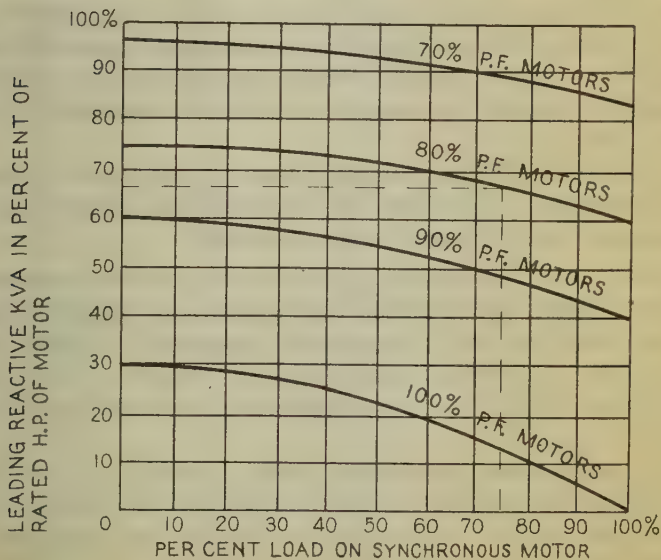


FIG. 18.—Showing approximate leading *kva.* drawn by high speed synchronous motors operating at partial loads with full-load excitation maintained.

Speed.—The speed of a synchronous motor is determined by the frequency of the supply current and the number of poles of the motor. Thus, the operating speed is constant for a given frequency and number of poles. The equation for determination of speed is:

$$r.p.m. = \frac{\text{frequency} \times 120}{P} \quad (1)$$

Where P = number of poles of the motor.

As all motors are built with an even number of poles, the available speeds on 60 cycles range from 3,600 *r.p.m.* for a two pole machine down to 80 *r.p.m.* for a machine containing 90 poles. This allows the motor to be directly connected to its load, even at lower speeds, where induction motors cannot be used advantageously on account of low operating efficiency and power factor.

If equation (1) be solved with respect to the *r.p.m.* at standard frequencies, inserting various number of even poles, the table shown on page 261 will be obtained.

Some motors are required to operate at more than one speed, but are constant speed machines at a particular operating speed. When a speed ratio of 2:1 for example is required, a single frame, two-speed synchronous motor may be suitable. Four-speed motors are used when two speeds not in the ratio of 2:1 are desired.

The single-frame, two-speed motor is usually of a salient-pole type construction with the number of poles corresponding to the low speed. High speed is obtained by regrouping the poles so as to obtain two adjacent poles of the same polarity, followed by two poles of opposite polarity. This gives the effect of reducing the number of poles on the rotor by one-half for high speed operation. Corresponding changes in the stator

Synchronous Speeds Possible at Various Frequencies

Poles	60 Cycles	50 Cycles	40 Cycles	25 Cycles
2	3600	3000	2400	1500
4	1800	1500	1200	750
6	1200	1000	800	500
8	900	750	600	375
10	720	600	480	300
12	600	500	400	250
14	514.2	428.6	343	214.3
16	450	375	300	187.5
18	400	333.3	266.6	166.6
20	360	300	240	150
22	327.2	272.7	218.1	136.3
24	300	250	200	125
26	277	230.8	184.5	115.4
28	257.1	214.2	171.5	107.1
30	240	200	160	100
32	225	187.5	150	93.7
34	212	176.5	141.1	88.2
36	200	166.6	133.3	83.3
38	189.5	157.9	126.3	78.9
40	180	150	120	75
42	171.5	142.8	114.2	71.4
44	163.5	136.3	109	
46	156.6	130.5	104.3	
48	150	125	100	
50	144	120	96	
52	138.5	115.4	92.3	
54	133.3	111.1	88.9	
56	128.6	107.2	85.7	
58	124.1	103.5	82.8	
60	120	100	80	
62	116.1	96.8	77.4	
64	112.5	93.7	75	
66	109	90.8	72.7	
68	105.9	88.2	70.6	
70	102.8	85.7		
72	100	83.3		
74	97.3	81		
76	94.7	78.9		
78	92.3	76.9		
80	90	75		
82	87.8	73.2		
84	85.7	71.4		
86	83.7			
88	81.8			
90	80			

connections are also made. This switching is usually accomplished automatically by means of magnetic starting, or manually operated pole changing equipment may be used.

Standard voltages of 220, 440, 550 and 2,200 are usually used for synchronous motors up to a rating of 200 *h.p.* Larger motors have standard voltage ratings of 2,300, 4,000, 6,600, 11,000 and 13,200.

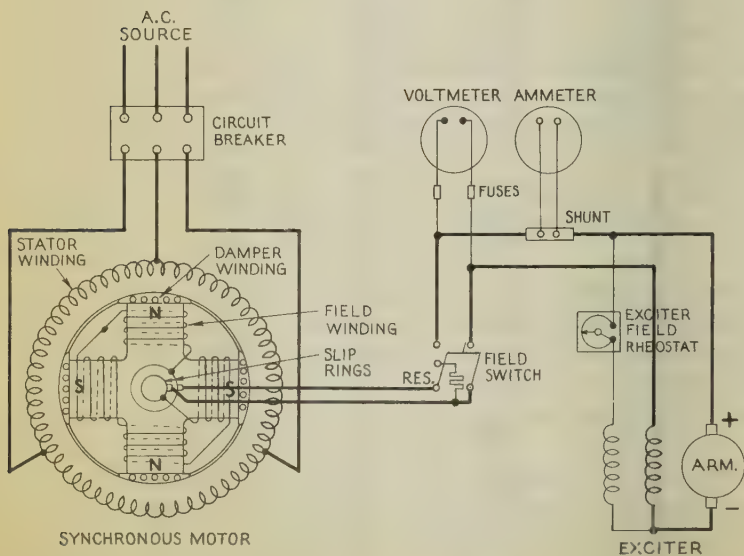


FIG. 19.—Showing exciter and synchronous motor connections with associated exciter field rheostat, field switch and meters.

Torques

General.—The torque required to operate the driven machine at every moment between the initial breakaway and the final shut-down is important in determining the motor characteristics.

The various torques associated with synchronous motors are termed as: *starting torque*, *running torque*, *pull-in torque* and *pull-out torque*.

Starting Torque.—The starting or breakaway torque required by the driven machine may be as low as 10%, as in the case of centrifugal pumps, and as high as 225 to 250% of full load torque as in the case of loaded reciprocating two-cylinder compressors.

The starting torque of a synchronous motor is the torque or turning effort (usually measured in pound-feet) which the motor develops when full voltage is applied to the armature winding.

The synchronous motor in itself has very little starting torque. With the modern motor, however, almost any reasonable torque can be obtained by the proper design of the damper windings (also called squirrel cage and amortisseur winding). The different values of starting torque are usually obtained by changes in the resistance and size of the damper windings. As a general rule, the starting inrush of current increases as the starting torques are increased.

Running Torque.—The running torque is determined by the horsepower and speed of the driven machine, and at any given point the torque in lb.-ft.

$$T = \frac{5,250 \times h.p.}{\text{speed in } r.p.m.} \quad (2)$$

The peak horsepower determines the maximum torque required by the driven machine. The motor must have a breakdown or a maximum running torque in excess of this figure in order to avoid stalling. Certain driven machines, like reciprocating compressors, have load torques which pulsate periodically.

To prevent excessive pulsation in the line current of the motor, proper flywheel effect (WR^2) must be provided either in the motor or the driven machine. In the case of synchronous motors, the flywheel effect must be made such that the natural frequency of the motor does not approximate the frequency of any impulses in the load torque. Natural frequency in cycles per minute:

$$f_n = \frac{35,200}{r.p.m.} \sqrt{\frac{Pr \times f}{WR^2}} \quad (3)$$

Where WR^2 = Weight in lb. $\times$ (radius of gyration in ft.)²
(motor and load).

$r.p.m.$ = Speed in revolutions per minute of motor.

f = Line frequency.

Pr = Synchronizing power of motor in kilowatts per electrical radian.

For calculation of WR^2 see pages 328 to 336.

Pull-in Torque.—When a synchronous motor has been started as an induction motor, it will run at from 2 to 5% below synchronous speed until the excitation is applied, at which time the rotor pulls into step. The amount of torque or load at which the motor will pull into step is called the *pull-in torque*.

Synchronous motors are usually designed for a definite application so the designer should know the nature of the load which the motor is required to start so that he can design the motor for the necessary starting and pull-in torque.

Pull-Out Torque.—When a synchronous motor is running in synchronism with no load, the individual field poles of the rotor have a fixed position with respect to the revolving magnetic field of the armature. When a mechanical load or resisting torque is applied to the shaft of the motor, it develops a torque to balance the requirements of the load torque. The increased torque requirement is produced by a backward shift or lag in the position of the field poles with respect to the revolving magnetic field. However, the rotor will maintain its synchronous speed.

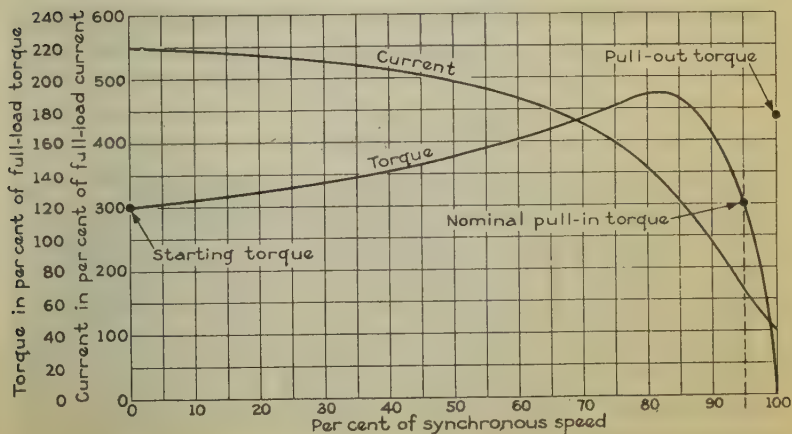


FIG. 20.—Speed-torque and speed-current characteristics of typical high speed synchronous motor.

When, due to the increased torque requirement, the field poles have shifted backward a distance approximately half the distance between adjacent poles, the motor is developing its maximum torque. Any further increase will cause the motor to pull out of step and stop. The maximum torque which the motor will develop without pulling out of step is called the "*pull-out torque*".

Power Factor

The power in watts delivered through a single phase A.C. circuit is the product of current, voltage and power factor. It is written:

$$W = EI \cos \phi \quad (4)$$

or
$$\cos \phi = \frac{W}{EI} \quad (5)$$

In a three phase A.C. circuit the power in watts is written:

$$W = EI \cos \phi \sqrt{3} \quad (6)$$

or
$$\cos \phi = \frac{W}{EI\sqrt{3}} \quad (7)$$

Since W represents the true power and the product EI the apparent power, the power factor may be defined as the ratio of the true and apparent power delivered through the circuit.

The fact that a synchronous motor always operates at a leading power factor or unity (100%) whereas an induction motor operates at a lagging power factor and receives its excitation from the line, has been made use of for power factor improvements. Employment of synchronous motors, therefore, assist to improve the plant operating power factor. In many cases they also cost less and have higher efficiencies than the corresponding induction motors. This is particularly true for low speed synchronous motors.

Many rate schedules incorporate a power factor clause, adjusting the rate according to power factor; others involve penalty or bonus if power factor is for example, below 90% or above 90% lagging.

A synchronous motor operating at full load and rated excitation delivers to the power system leading *kva.* equal to:

$$kva. = \frac{0.746 \times h.p. \text{ rating}}{Eff \times \cos \phi} \sqrt{1 - \cos^2 \phi} \quad (8)$$

It should be noted that at partial loads, and rated excitation, more leading *kva.* is supplied. Fig. 18 illustrates curves approximating the leading reactive *kva.* from synchronous motors at four different power factor ratings, at varying load conditions, based on maintaining full load rating power excitation at all loads.

Thus at three-quarter load, for example, a 100 *h.p.* 80% power factor synchronous motor driving an air compressor supplies leading reactive *kva* equal to approximately 66% of its horsepower rating, or 66 *rkva.* (See fig. 18.)

The unity power factor synchronous motor as shown in fig. 18 supplied leading reactive *kva.* only at part load, but at full load, although then providing no leading reactive *kva.*, it still improves the power factor by adding to the kilowatt load without increasing the reactive *kva.* load. A unity power factor synchronous motor costs less than a leading power factor synchronous motor of the same horsepower rating because less material is used in its windings and magnetic parts. Highest efficiency is also obtained with a unity power factor synchronous motor, but when considerable power factor improvement is required, leading power factor synchronous motors are generally preferable.

A simple approximate rule for estimating leading *kva.* requirement for power factor correction is as follows:

Each horsepower of 80% power factor synchronous motor, operating at full load and rated excitation, will supply the lagging reactive *kva.* for $1\frac{1}{3}$ *h.p.* high speed induction motors. Thus a 75 *h.p.* 80% power factor synchronous motor will correct to unity power factor approximately 100 *h.p.* in high speed induction motors.

Example on Power Factor Correction.—A three-phase transmission line supplies 100 *kw.* to a three-phase induction motor at 220 volt line potential and 80% power factor lagging current. At what power factor must a synchronous motor connected on the same circuit as the induction motor be operated if the line current taken by the synchronous motor is 234 amperes, and the power factor of the total load is to be made unity?

Solution.—It is first necessary to find the current drawn by the induction motor. This current will be obtained from the formula for three-phase power, which is:

$$KW = EI \cos \phi \sqrt{3} \times 10^{-3} \quad (9)$$

which equation if solved with respect to the current gives:

$$I = \frac{100,000}{220 \times 0.8 \times \sqrt{3}} = 328 \text{ amperes}$$

With reference to vector diagram, fig. 21, it is evident that side *BC* in triangle *ABC* equals $328 \times 0.6 = 196.8$ amperes. and

$$\sin \phi_m = \frac{196.8}{234} = 0.84 \text{ and } \phi_m = 57^\circ$$

Hence, the synchronous motor should be operated at a power factor of 0.54 to obtain unity power factor of the total load.

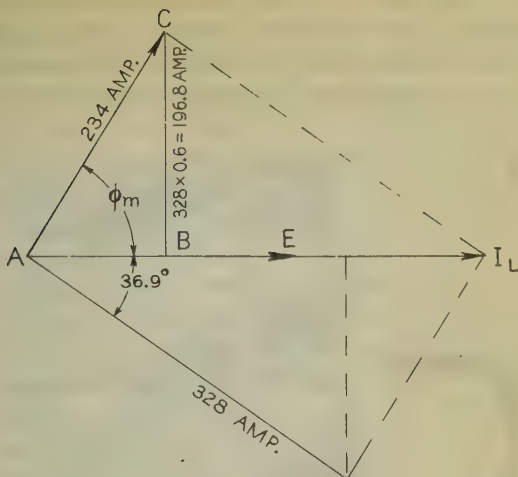


FIG. 21 - Vector diagram showing method used to calculate power factor.

Control of Synchronous Motors

General.—To make a synchronous motor self-starting a squirrel cage winding is usually placed on the rotor of the machine. After the motor comes up to speed which is slightly less than synchronous, the rotor is energized. When synchronous motors are started, their direct current fields are not excited until the rotor has reached practically full synchronous speed. The starting torque required to bring the rotor up to this speed is produced by induction.

In addition to the direct current winding on the field of synchronous motors, they are generally provided with a *damp*er or *amortissuer winding* consisting of short-circuited bars of brass

or copper joined together at either end by means of end rings and embedded in slots in the pole faces. This winding, usually termed *squirrel cage winding*, enables the motor to obtain sufficient *starting torque* for the motor to start under load.

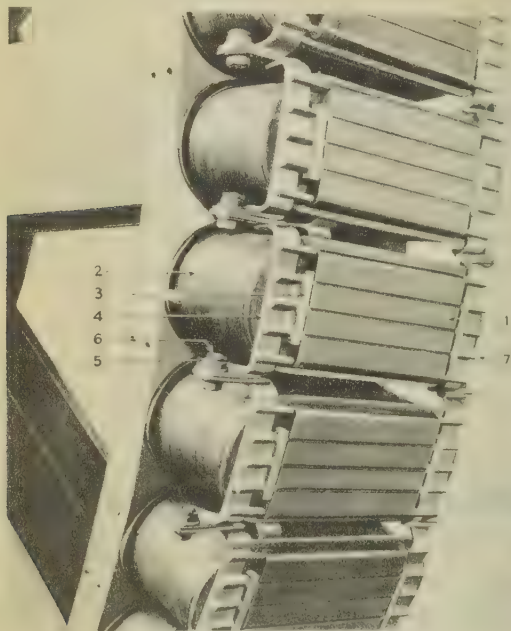


FIG. 22.—Illustrating detail of poles and squirrel cage winding of a low speed synchronous motor with high starting torque characteristics. The squirrel cage winding consists essentially of a number of metal rods or bars passing through the pole *1* in axial direction. These rods, which vary in number and conductivity according to the work to be done, are placed so as to produce the necessary starting and pull-in torque required by the particular drive for which it is intended, as well as to produce uniform accelerating torque. Both ends of the rods pass through and are silver soldered to short-circuiting end segments *7*. The end segments of each pole are connected to the corresponding segments of the next pole *5* to form the "squirrel cage" winding. Either directly or by means of link type construction, they form continuous short circuiting rings, one on each side of the spider rim. (Courtesy Allis-Chalmers Manufacturing Co.)

The starting torque which is sufficient to bring the motor up to synchronous speed is termed *pull-in torque*.

The maximum torque which the motor will develop without pulling out of step is termed the *pull-out torque*.

When in a synchronous motor the stator winding is being excited by the A.C. line connection, it immediately sets up the rotating magnetic field (see figs. 4 to 16). The rotating flux of this field cuts across the damper winding of the rotor and induces secondary currents in the bars of this winding.

The reaction between the flux of these secondary currents and that of the rotating stator field produces the torque necessary to start the rotor in motion and bring it up to speed.

As the motor has been brought up to nearly synchronous speed (as an induction motor because of the damper winding) then the direct current field poles are excited and the strong flux of these poles cause them to be drawn into step or full synchronous speed with the poles of the rotating magnetic field of the stator.

At normal operation, the rotor continues to revolve at synchronous speed as if the direct current poles were locked to the poles of the rotating magnetic field of the stator.

Because of the fact that a synchronous motor has no slip after the rotor is brought up to full speed, no secondary currents are induced in the bars of the damper windings during normal operation.

In starting the synchronous motor as an induction motor, the voltage impressed upon the motor should be reduced in starting while coming up to speed. This reduced starting voltage is usually obtained from a starting compensator (auto-transformer) similar to that used in the starting of an induction motor.

When this method of starting is used, the usual practice is to close the starting contactor first, connecting the stator to the reduced voltage. When a speed at near synchronism has been reached, the starting contactor is opened and the running contactor is closed, thus connecting the motor to the full line voltage.

After synchronous speed has been reached, the field switch is closed through a moderate amount of resistance. The field current may now be adjusted to make the motor operate at the desired power factor.

It is customary in cases where the motor must operate at a high starting torque, to use full line starting voltage in connection with a time-delay over-current relay which will become operative before the windings can be damaged by the surge of starting current.

Starting Methods.—Methods most commonly used in synchronous motor starting are as follows:

1. Across the line starting.
2. Reduced voltage starting.
3. Reactance starting.
4. Resistance starting.
5. Korndorfer method of starting.

Across the line method of starting, consists simply in closing the main line switch either manually or by means of a push button arrangement and use of a magnetic type of starter or circuit breaker.

After synchronous speed has been attained the field current is applied as previously described. This method of starting should always be adhered to unless the driven machine requires two or more increments of starting torque, or the power system

limitation requires a starting current below that of the full voltage surge.

An automatic across the line starting synchronous motor wiring arrangement is shown in fig. 23, with its elementary diagram in fig. 24. The operation and function of the devices as shown in fig. 24 are as follows: Pushing the start button energizes the line contactor coil LE , closing the line contactor and connecting L_1 , L_2 and L_3 to the motor. The interlock LE closes at the same time as the line contactor and forms a holding circuit for the line contactor, so that the push button may be released.

While the motor is accelerating the field circuit is closed through the normally closed pole F_3 , of the field contactor, through the discharge resistor and the retarding coil FR of the field relay. This holds the interlock FR open until the motor approaches synchronism. At the time the line contactor LE closes, the contactor coil FR is energized and tends to close the interlock FR .

As the motor accelerates, the induced field current through the retarding coil FR decreases, and releases the interlock FR when the motor nears synchronism. After a few seconds' delay the interlock FR closes, energizing the field contactor coil F , causing F_1 and F_2 to close and F_3 and F_4 to open. The closing of F_1 and F_2 applies excitation to the motor field, completing the starting operation. The opening of F_3 opens the discharge circuit of the motor field.

Operation of the stop button or the overload relay at any time opens the control circuit and the contactors open, disconnecting the motor from the line.

Some exciters have a tendency to build up voltage slowly; because of this fact, the field contactor is equipped with a normally closed interlock which may be used to short circuit

the exciter field rheostat, thus causing the exciter voltage to build up more quickly.

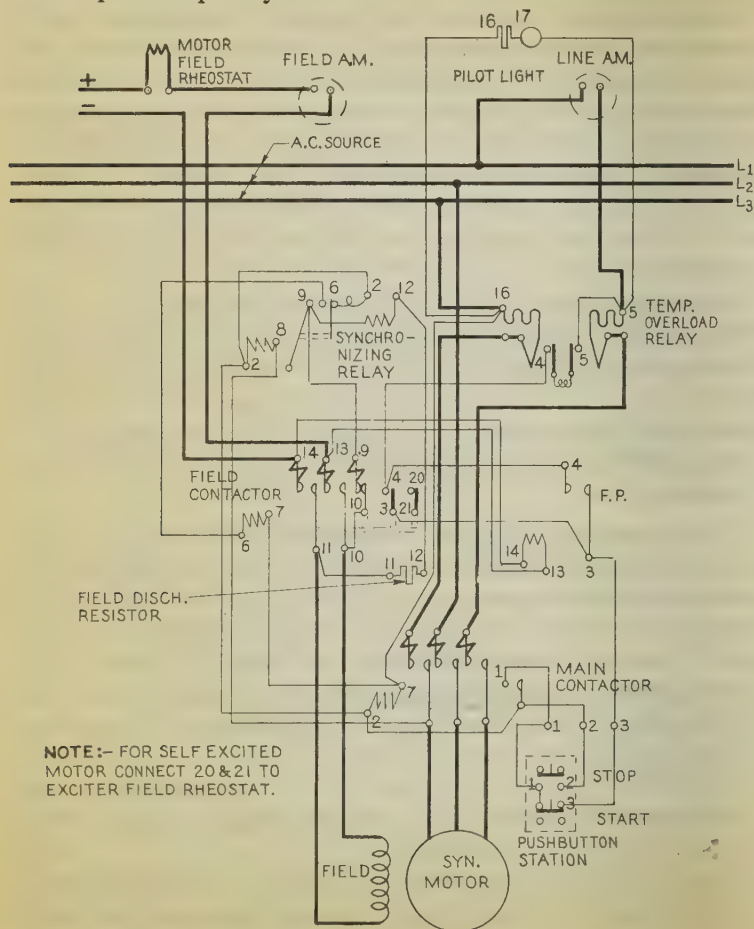
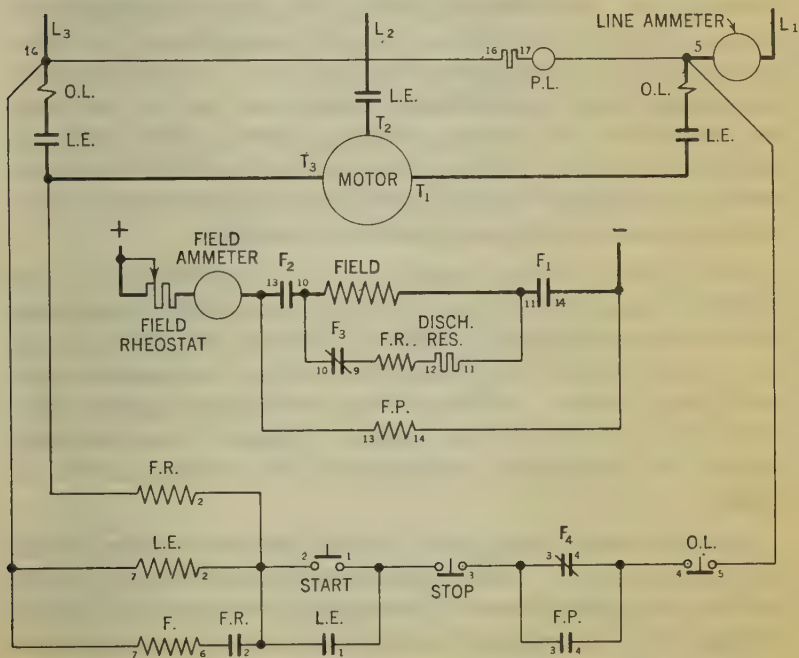


FIG. 23.—Panel wiring diagram of a typical automatic across the line synchronous motor starter.

Power company rules usually limit the starting current which may be drawn by a motor. There are two types of such rules, one type specifying the allowable number of amperes for each horsepower rating. The more recent "*Increment*" type of rules is based upon the "*capacity to serve*" a given installation. Usually the total current is not limited, but must be taken in increment steps, the magnitude of each step being determined by the total connected load.



ELEMENTARY DIAGRAM

Fig. 24.—Elementary diagram for across the line synchronous motor starter whose panel wiring diagram is shown in fig. 23.

Reduced voltage starting differ from the across the line method in that reduced voltage is first applied to the motor by means of a transformer (usually an auto-transformer). In this method of starting, full voltage is applied only after the motor has reached nearly synchronous speed, at the reduced voltage.

Various methods of manual reduced voltage starting are shown in figs. 25 to 30.

The starting method shown in fig. 25 utilizes three switches or contactors. Here the two starting oil switches or contactors are connected to each side of the auto-transformer or compensator and are both closed at the same time. After the motor has attained nearly synchronous speed, the starting switches are opened and the running switch is closed. Most starting arrangement of this type are equipped with electrical or mechanical interlocks in order to prevent any manipulating of the switches, except in the pre-described sequence.

The starting method shown in fig. 26 consists of two oil switches or contactors. Here the running switch is closed after the motor speed becomes constant, connecting the motor to the line. The starting switch then opens, being interlocked with the running switch. As soon as the speed again becomes constant, the field switch (not shown) is closed. The controller remains in the running position until the running switch is tripped.

Another synchronous motor starting method is represented in diagram, fig. 27. In this starting method switches #1 and #2 are first closed simultaneously connecting the motor to the line through the star-connected auto-transformers. Power is then supplied to the motor at a reduced voltage. Switch #1 is opened as soon as the speed becomes constant, and switch #3 closes instantly, being electrically interlocked with switch #1.

This connects the motor directly across the line, the terminal voltage having increased to normal without dropping to zero.

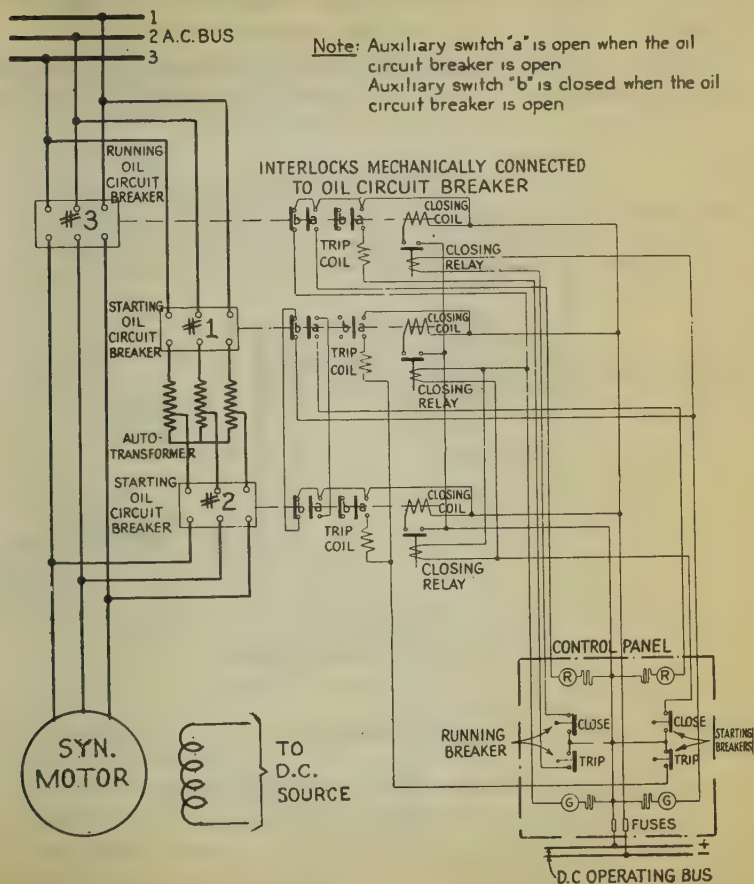


FIG. 25.—Reduced voltage starting method of large synchronous motor using three oil circuit breakers.

Switch #2 is interlocked with switch #3 so that it opens immediately after switch #3 closes. The field switch is closed as soon as the speed again becomes constant. The motor is stopped by switch #3 and the field switch is then opened.

A manual synchronous motor starting method utilizing two circuit breakers enclosed in one tank is represented in fig. 28.

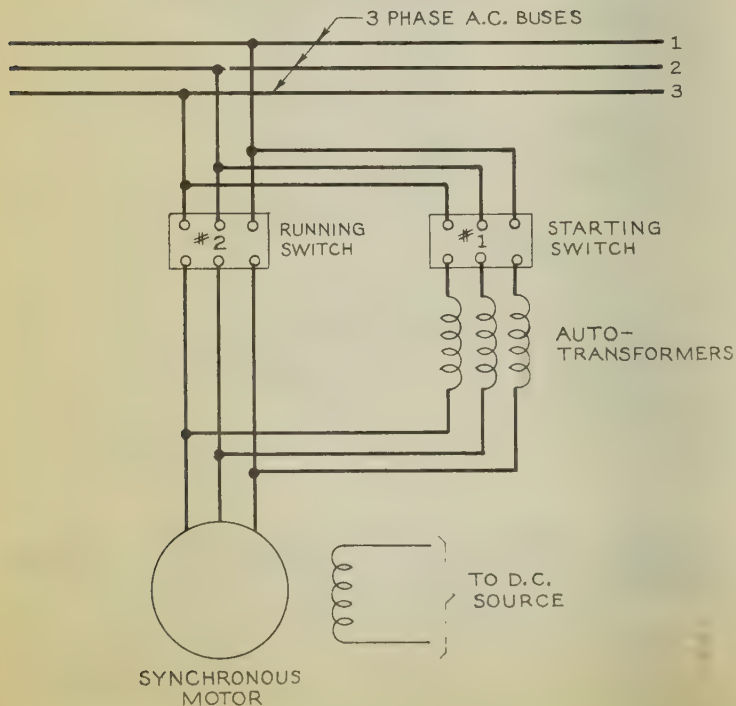


FIG. 26. Reduced voltage starting of synchronous motor with two oil circuit breakers or contactors.

With this arrangement the two auto-transformer coils are short circuited at starting and the reduced voltage is supplied from the transformer taps as indicated.

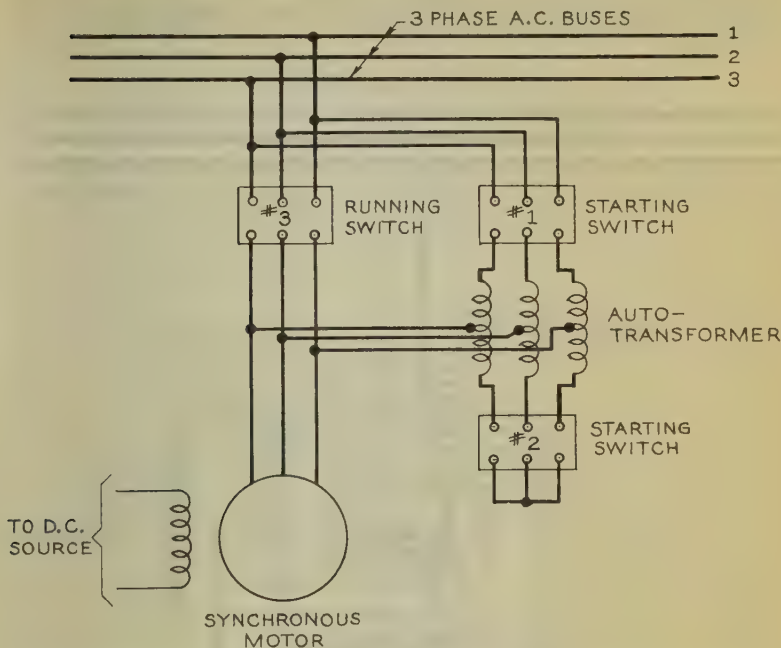


FIG. 27.—Showing connections for autotransformer synchronous motor starting, using three oil circuit breaker or contactors.

The auto-transformers are usually supplied with several taps in order to provide a suitable range of starting torque.

Reactance motor starting is similar to the previously discussed reduced voltage starting methods, except that the first step is obtained by reactance in series with the motor armature instead of auto-transformers. In the reactance method of

starting, more current is required from the line for the same torque on the first step, than when compensators are used. It has an advantage, however, in that no circuit opening is required when the motor is transferred to running voltage, the transfer being accomplished by a short circuiting of the reactance.

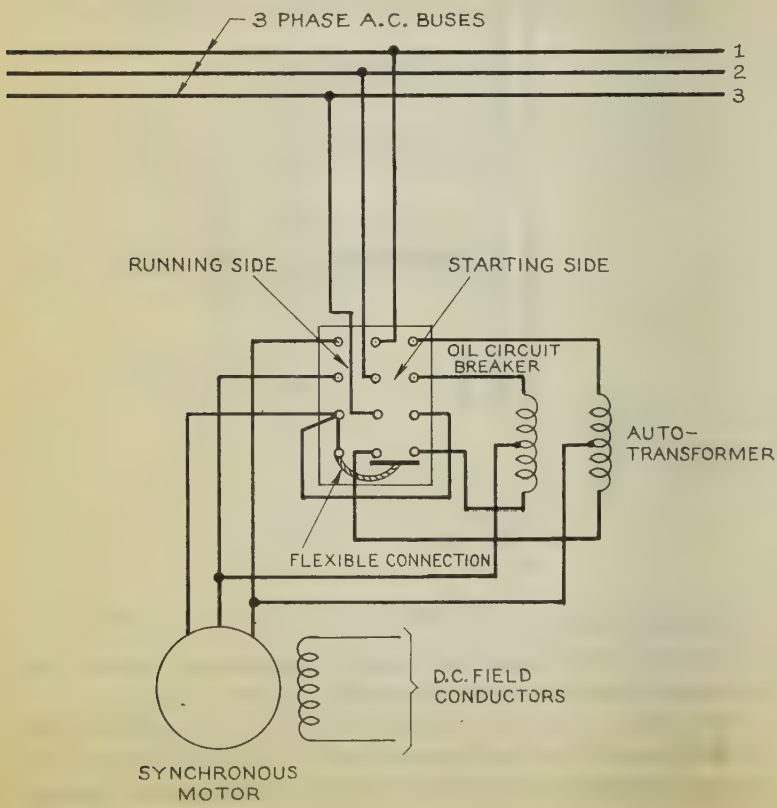


FIG. 28.—Synchronous motor reduced voltage starting employing a starting and running type oil circuit breaker.

A typical circuit diagram using the resistance method of reduced voltage starting is shown in fig. 29. Here switch #1 is closed first, connecting the motor to the line through the whole resistance. Switches #2, #3 and #4 are then closed, with a time interval between each closing, each switch in turn short circuiting a part of the resistance.

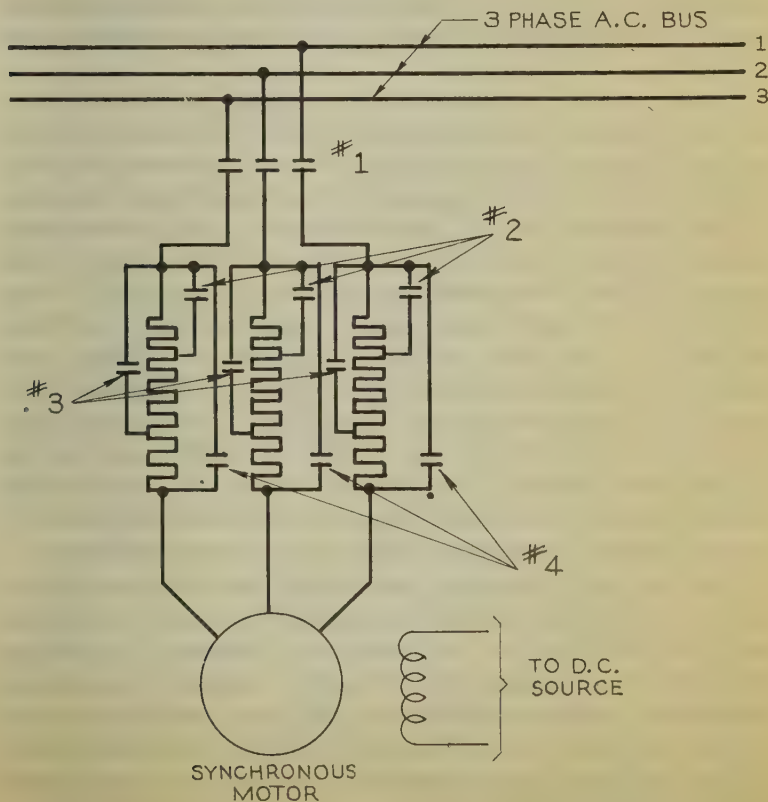


FIG. 29.—Schematic wiring arrangement of a resistance type synchronous motor starter.

This method of starting is sometimes used when due to power company rulings "increment" starting is required to provide several progressive steps of starting current.

In common with the reactance and resistance method of starting, the Korndorfer method permits the motor being started without the opening of the motor circuit. By this method the motor is first connected through suitable taps of a compensator and then started by connecting the compensator to the line.

The connection to full voltage is accomplished by first opening the neutral of the starting compensator, allowing the motor to run with a part of the compensator winding in series with the motor, and then short circuiting the entire compensator winding.

With reference to fig. 30, showing a typical Korndorfer starting method, switch or contactor #1 is first closed, thus connecting one of the compensator windings to the line. Then switch #2 is closed completing the motor circuit at reduced voltage. As the motor increases its speed, a timing relay operated by switch #2 opens the circuit of #3, which in turn opens the transformer neutral. Switch #4 is next closed, connecting the motor to full line voltage by short circuiting the compensator sections. By opening switch #2, the reduced voltage taps of the compensator are disconnected and the permanent running connection to the motor is being completed.

Part winding starting is sometimes used on synchronous motors. When this method is being used the motor is equipped with various taps on the armature connected to suitable switches. One arrangement of this sort consists in making a two-circuit armature winding such that one circuit can be used to start the motor while the other is being left disconnected. This second winding is connected after the motor has accelerated a required amount.

Other methods of synchronous motor starting is by means of an auxiliary prime mover usually on induction motor. This method of starting is applied to motors having no squirrel cage winding, or to alternators converted to motor use. With this method the motor can carry no mechanical load while starting.

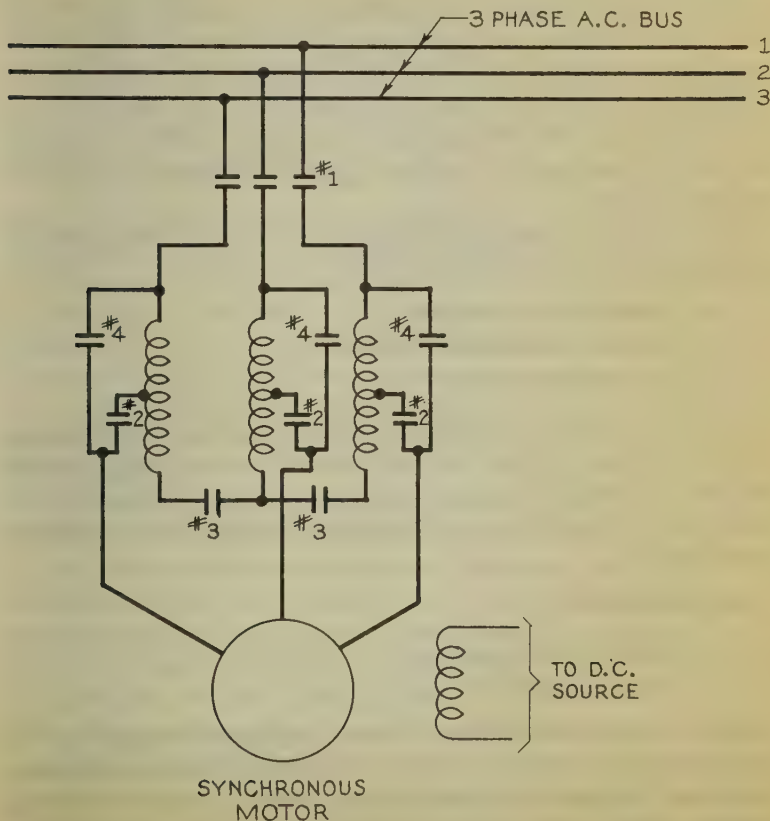


Fig. 30.—Schematic wiring representation of Korndorfer starting method of synchronous motor.

Application of Synchronous Motors

The correct selection and application of a motor involves a great many factors affecting the installation, operation and subsequent servicing of the motor. In most cases, the answer to a number of the problems thus involved are obvious, while in other instances the answers are supplied in whole or part by certain intermediaries such as the manufacture of motor equipped devices.

The various classes of service for which synchronous motors are used may be classified as follows:

1. Power factor correction.
2. Constant speed-load drives.
3. Voltage regulation.

On power systems employing a large number of induction motors and other devices having a lagging power factor such as welders, fluorescent lights, etc., the power factor may be improved by installation of devices operating with a leading power factor.

Such devices are:

- (a) Synchronous motors.
- (b) Static condensers.

When synchronous motors are employed exclusively as power factor correction devices, they are termed *synchronous condensers*, because the effect on the power system is the same as that of a static condenser which also produces a leading current.

The power factor of a synchronous motor may be varied by adjustment of the field current. Thus, by adjusting the field current, the power factor may be varied in small steps from low lagging power factor to a low leading power factor. This makes it possible to vary the power factor over a considerable range and places the characteristics of the motor under the immediate control of the operator at all times.

Because of the higher efficiency possible with synchronous motors, they can be used advantageously on most loads where constant speed is required.

Typical applications of *high-speed* synchronous motors (above 500 *r.p.m.*) are such drives as: Centrifugal pumps, D.C. generators, belt driven reciprocating compressors, fans, blowers, line shafts, centrifugal compressors, rubber and paper mills, etc.

The field of applications of *low-speed* synchronous motors (below 500 *r.p.m.*) are drives such as: Reciprocating compressors (largest field of use), Jordan engines, centrifugal and screw-type pumps, ball and tube mills, vacuum pumps, electroplating generators, line shafts, rubber and band mills, chippers, metal rolling mills, etc.

Synchronous motors are rarely used in sizes below 20 *h.p.* Principal field of application are in sizes of 100 *h.p.* and larger.

Another field where synchronous motors are suitable is that of *voltage regulation*. At the ends of long transmission lines, the voltage has a tendency to vary greatly, especially if large inductive loads be present. If the inductive load be thrown off, then, due to the capacity effect or condenser action of the line, the voltage may rise considerable above normal. By installing a synchronous motor with a voltage regulator to control its field, the voltage change on the line may be controlled. The action of the voltage regulator is such that when the voltage drops due to inductive load, the field strength of the synchro-

nous motor is increased; this raises the power factor and maintains the voltage at the same value.

If the voltage tends to raise due to the capacity effect of the line, the regulator weakens the field and causes the motor to have a lagging or inductive load so as to hold the voltage to normal.

CHAPTER 9

The Squirrel Cage Motor

General.—The most common form of induction motor is the “*squirrel cage*” type. This motor has derived its name from the fact that the rotor or secondary resembles the wheel of a squirrel cage. Its universal use lies in its mechanical simplicity, its ruggedness, and the fact that it can be manufactured with characteristics to suit most industrial requirements.

Construction.—With reference to figs. 1 and 2, a squirrel cage motor consists essentially of two units, namely:

1. Stator, and
2. Rotor.

The stator or primary consists of a laminated sheet steel core with slots, in which the insulated coils are placed. The coils are so grouped and connected as to form a definite polar area and produces a rotating magnetic field when connected to a polyphase alternating current circuit.

The rotor or secondary is also constructed of steel laminations, but the windings consist of conductor bars placed approximately parallel to the shaft and close to the rotor surface.

These windings are short circuited or connected together at each end of the rotor by a solid ring. The rotors of large motors have bars and rings of copper connected together at each end by a conducting end ring made of copper or brass. The joints between the bars and end rings are usually electrically welded into one unit, with blowers mounted on each end of the rotor. In small squirrel cage rotors, the bars, end rings and blowers are of aluminum casted in one piece instead of welded together.

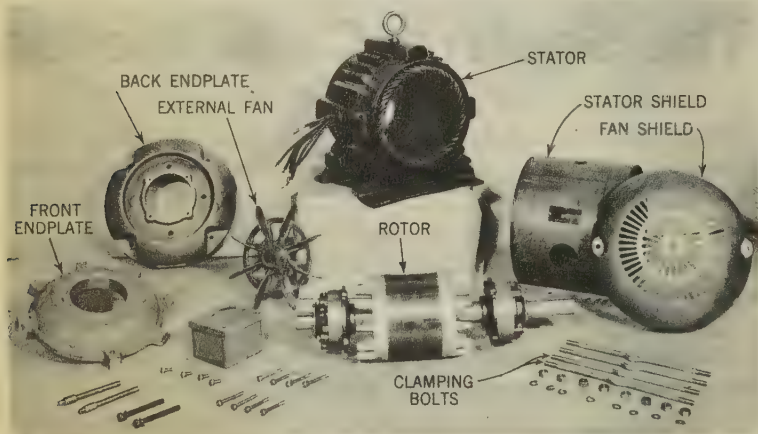


FIG. 1.—Showing principal parts of totally enclosed fan-cooled squirrel cage induction motor.
(Courtesy Wagner Electric Corp.)

The air gap between the rotor and stator must of necessity be very small in order to obtain the best possible motor efficiency and power factor. The shaft must, therefore, be very rigid and furnished with the highest grade of bearings, being usually of the sleeve or ball-bearing type.

Principles of Operation.—In a squirrel cage motor the secondary or squirrel cage winding takes the place of the field winding

in a synchronous motor. As in a synchronous motor a rotating magnetic field is set up by the currents in the stator. This field is set up by the rising and falling currents in the windings. When the current rises in the first phase, a magnetic field is produced by only the first winding. As the current decreases in this and increases in the second, the magnetic field shifts along a little until it is all produced by the second winding. When the third winding has a maximum current the field is shifted a little more. The windings are so distributed that this shifting is uniform and continuous. It is this action which produces a *rotating magnetic field*.*

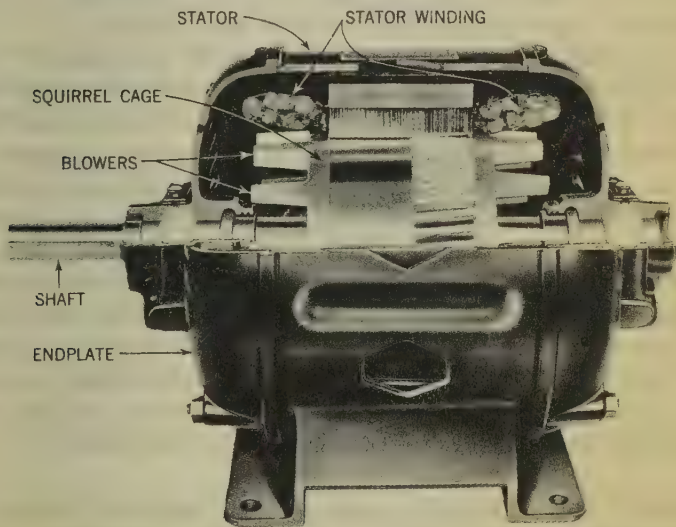


FIG. 2.—Showing cut-away view of typical squirrel cage induction motor. (Courtesy Wagner Electric Corp.)

*NOTE.—For a complete analysis of the rotating magnetic field see pages 250 to 256.

As this field rotates, it cuts the squirrel cage conductors and voltages are set up in these just as though the conductors were cutting in the field as in the case of the direct current generator. These voltages cause currents to flow in the squirrel cage circuit; through the bars under the *north poles* into the end ring, back through the bars under the adjacent *south poles*, into the other end ring and the circuit is completed back to the original bars under the *north poles*.

The current flowing in the squirrel cage, down one group of bars and back in the adjacent group, makes a loop which establishes magnetic fields in the rotor core with *north* and *south poles*. This loop consists of one turn, but there are several conductors in parallel and the currents may be large.

These poles in the rotor are attracted by the poles of the rotating field set up by the currents in the armature winding, and follow them around in a manner similar to that in which the field poles follow the armature poles in a synchronous motor.

There is, however, one very interesting and important difference between the synchronous motor and the induction motor; *the rotor of the latter does not rotate as fast as the rotating field in the armature*. If the squirrel cage were to go as fast as the rotating field, the conductors in it would be standing still with respect to the rotating field rather than cutting across it. Then there could be no voltage induced in the squirrel cage, no currents in it, no magnetic poles set up in the rotor, and no attraction between it and the rotating field in the stator.

Speed.—The speed of a squirrel cage induction motor is nearly constant under normal load and voltage conditions, but is dependent on the number of poles and the frequency of the alternating current source. In the case of a squirrel cage motor, however, the motor slows down when loaded an amount

just sufficient to produce the increased current to meet the required torque.

The difference in speed for any given load between synchronous and load speed, is called the "*slip*" of the motor. This slip is usually expressed as a percentage of the synchronous speed.

Since the amount of slip is dependent upon the load, the greater the load, the greater the slip will be, that is, the slower the motor will run. This slowing down of the motor, however, is very slight even at full load, and amounts to from 1 to 4% of synchronous speed. Thus, the squirrel cage type is considered to be a constant speed motor.

The slip of an induction motor, as previously defined, is the difference between its synchronous speed and its operating speed and may be expressed in the following manner:

- (a) As a percentage of synchronous speed.
- (b) As a decimal fraction of synchronous speed.
- (c) Directly in revolutions per minute.

The most common method used for speed calculation of induction motors is by the use of the well known formula:

$$\text{Slip (\%)} = \frac{(\text{Synch. speed} - \text{operating speed}) 100}{\text{Synch. speed}}$$

The synchronous speed of a motor is found by the following:

$$N_s = \frac{\text{frequency} \times 120}{\text{number of poles}}$$

Example.—A three-phase squirrel cage induction motor having 4 poles is operating on a 60-cycle A.C. circuit at a speed of 1,728 revolutions per minute. What is the slip of this motor?

Solution. - By substituting our values in the previously given formulae, we obtain:

$$\text{Synchronous speed, } N_s = \frac{60 \times 120}{4} = 1,800 \text{ r.p.m.}$$

$$\text{Slip} = \frac{(1,800 - 1,728) 100}{1,800} = 4\%$$

From the foregoing it follows that this type of motor is not suitable in industrial applications where a great amount of speed regulation is required, because the speed can only be controlled by a change in frequency, number of poles or slip.

Changing the frequency is done only rarely, as with electric ship propulsion, when the motors are the only load on the alternator. The poles are sometimes changed by either using two or more distinct windings or reconnecting the same winding for different number of poles.

Torque.—The starting torque of a squirrel cage induction motor is the turning effort or torque which the motor exerts when full voltage is applied to the motor terminals at the instant of starting. The amount of starting torque which a given motor develops depends within certain limits on the resistance of the rotor winding. Starting torque is usually expressed as a per cent of full load torque. An increase of rotor resistance gives an increase in starting torque, with a corresponding increase in slip and a decrease in efficiency. In fact, all the desirable characteristics are so inter-related, that it is impossible to make one of them surpassingly good without adversely affecting the others.

Motors can be built for high efficiency alone, or high starting torque or high power factor, but there is a commercial limit which prohibits a motor from excelling in all characteristics.

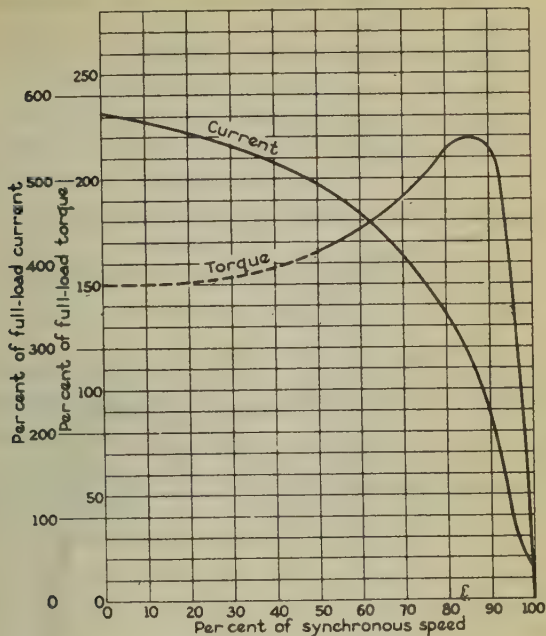


FIG. 3.—Characteristic curves of a normal starting torque, low starting current, squirrel cage motor.

In order to have a basis for normal starting torques, The National Electrical Manufacturers Association has established minimum values for motors from 2 poles to 16 poles, inclusive.

With full rated voltage applied at the instant of starting, the starting torques will not be less than the following, expressed in percentages of full load torque:

2	pole,	150%	of full load torque				
4	"	150%	" " " "				
6	"	135%	" " " "				
8	"	125%	" " " "				
10	"	120%	" " " "				
12	"	115%	" " " "				
14	"	110%	" " " "				
16	"	105%	" " " "				

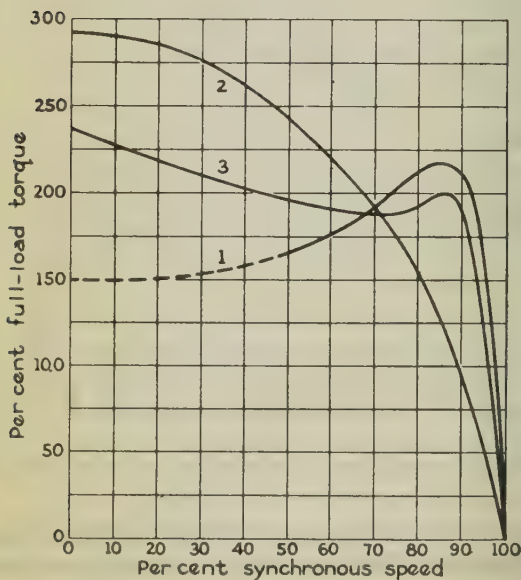


FIG. 4.—Speed-torque characteristics of three classes of squirrel cage motors. Curve 1 represents a normal starting torque, low starting current motor. Curve 2 represents a high starting torque, high slip motor. Curve 3 is a high starting torque low starting current motor.

Classification of Squirrel Cage Motors

Squirrel cage motors are further classified by NEMA according to their electrical characteristics as follows:

1. *Class A*—Normal torque, normal starting current motors.
2. *Class B*—Normal torque, low starting current motors.
3. *Class C*—High torque, low starting current motors.
4. *Class D*—High slip motors.
5. *Class E*—Low starting torque, normal starting current motors.
6. *Class F*—Low starting torque, low starting current motors.

Class A Motors.—This is the most popular of all types, employing a squirrel cage winding having relatively low resistance and reactance. It has a normal starting torque and low slip at the rated load and may have sufficiently high starting current to require, in most cases, a compensator or resistance starter for motors above $7\frac{1}{2}$ h.p.

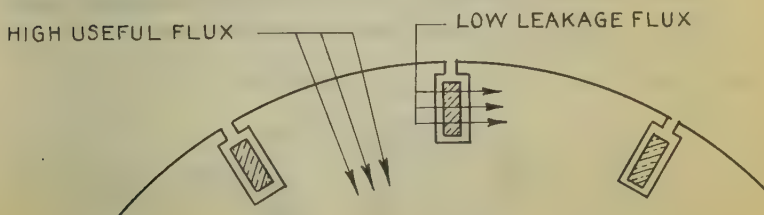


FIG. 5.—Illustrating rotor construction to obtain normal torque with normal starting current. In this type the rotor bars are placed close to the surface of the rotor. Rotor reactance is relatively low. (*Class A*.)

Class B Motors.—These are built to develop normal starting torque, with relatively low starting current, and can be started at full voltage. The low starting current is obtained by the design of the motor to include inherently high reactance. The combined effect of induction and frequency upon the current is termed inductive reactance. The slip at rated loads is relatively low.

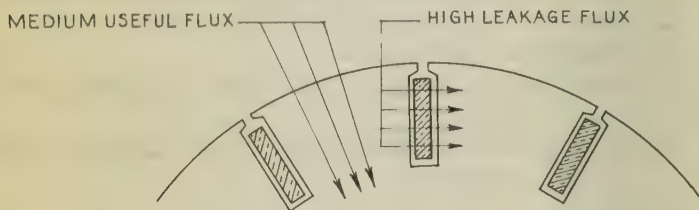


FIG. 6.—To obtain normal torque, with low starting current, the rotor is constructed with deep and narrow rotor bars; this form serving to produce high reactance during starting. (*Class B.*)

Class C Motors.—These are usually equipped with a “double squirrel cage winding” and combine high starting torque with a low starting current. These motors can be started at full voltage. The low starting current is obtained by design of motors to include inherently high reactance. The slip at rated load is relatively low.

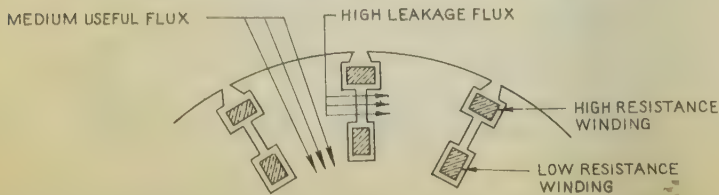


FIG. 7.—In this type of rotor construction two sets of bars are used. The outer rotor bars with high resistance produce high starting torque with low starting current. At normal speed more of the rotor current flows in the inner windings. (*Class C.*)

Class D Motors.—They are provided with a high resistance squirrel cage winding, giving the motor a high starting torque, low starting current, high slip (15 to 20%), low efficiency.

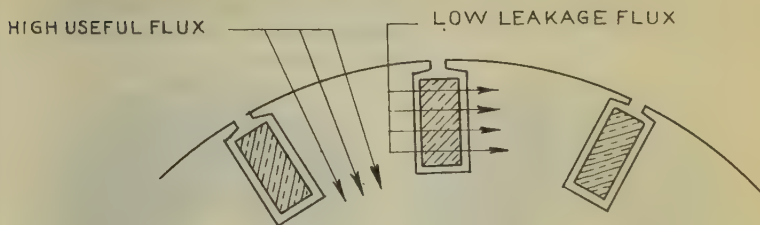


FIG. 8.—Illustrating rotor construction of a high slip motor. To obtain low starting torque with low starting current, thin rotor bars are used to make the leakage flux of the rotor low and the useful flux high. (Class D.)

Class E Motors.—They have a low slip at rated load. The starting current may be sufficiently high as to require a compensator or resistance starter above $7\frac{1}{2}$ h.p.

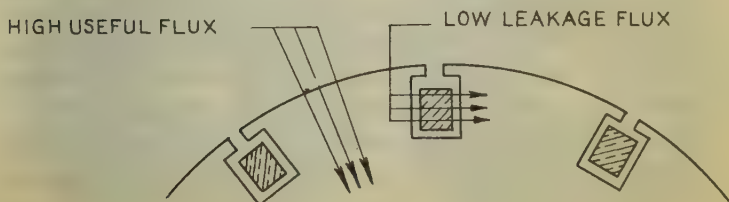


FIG. 9.—In this type rotors are constructed with a low resistance winding, which is placed to give low reactance. (Class E.)

Class F Motors.—These combine a low starting current with a low starting torque and may be started on full voltage. The low starting current is obtained by design of the motor to include inherently high reactance.

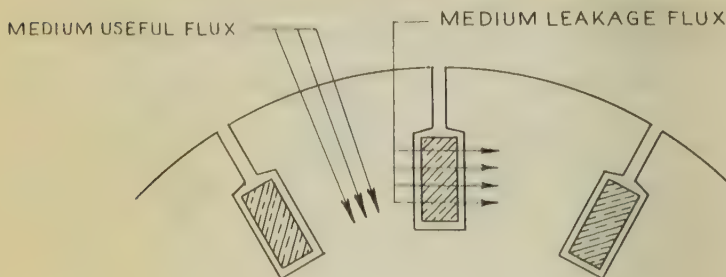


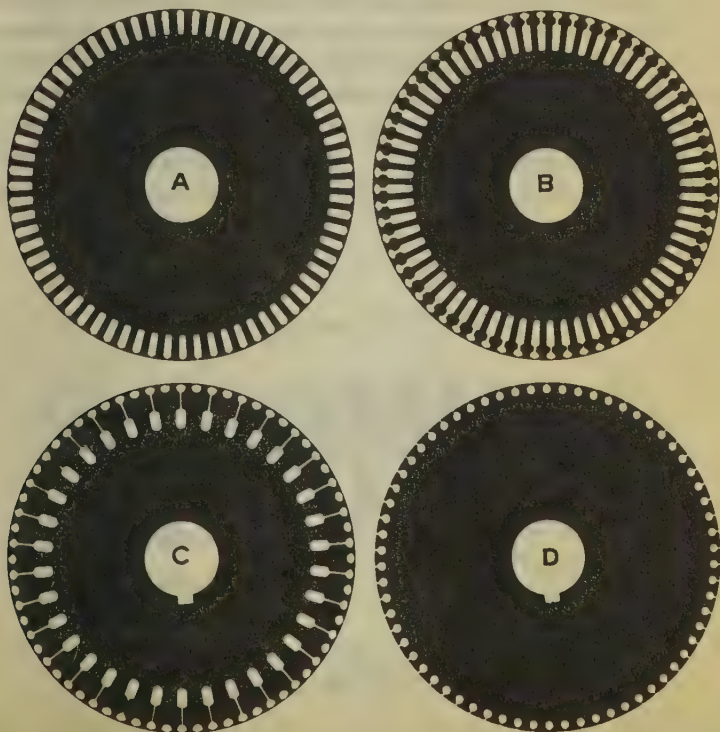
FIG. 10. —Showing rotor construction in a low starting torque low starting current motor. In this type a low resistance rotor winding is placed to give high reactance during the starting period. (Class F.)

Double Squirrel Cage Motor.—This motor is so termed because it is designed with two separate squirrel cage windings, one within the other. Thus a motor of this type is a combination of one having both a high and low resistance squirrel cage winding. The outer cage winding is made of high resistance material, while the inner cage winding is made of a metal having a low resistance.

In starting, the former serves to give the motor a high torque, while at full load speed the latter carries most of the current.

An example illustrating how the two squirrel cages operate is shown in figs. 15 and 16. From the shape of the rotor slots, it is apparent that the bars of the inner cage are

surrounded entirely by iron except for the constricted portion of the slot between the two cages which constitutes an air gap. The bars of the outer cage are surrounded by iron only at the sides and have two air gaps in the magnetic path around them, that is, this path is much less perfect magnetically than that around the inner conductors, or in other words, its inductance is lower.



FIGS. 11 to 14.—Showing typical rotor laminations for classes *A*, *B*, *C* and *D* squirrel cage induction motors. (Courtesy General Electric Co.)

Fig. 15 shows the conditions just as the motor is ready to start. At this instant the revolving field produced by the stator current is sweeping across both sets of rotor conductors at the full line frequency and inducing currents in them. Since the outer conductors have a relatively low inductance, considerable current is set up in them even at full line frequency.

In the inner conductors the current is greatly impeded, however, by the combined action of the higher inductance of this winding and the high frequency of the current, in fact the choking action of the self-induction at line frequency is so great that but little current can flow through this winding at the start. The relative density of the currents in the two sets of conductors is shown by their depth of shading.

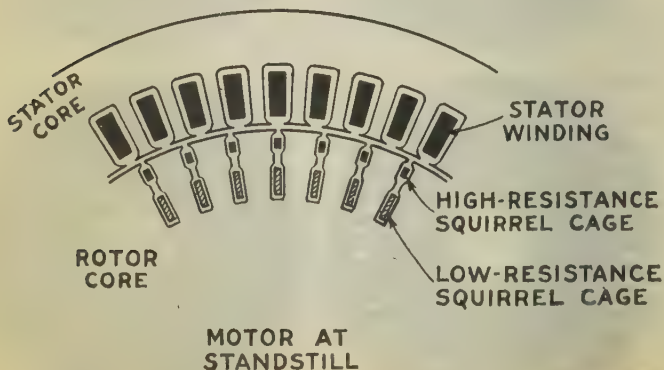


FIG. 15.—Section showing stator and rotor current relations in a *double squirrel cage induction motor* at the instant when the current is applied and the motor is about to start. The high resistance cage carries most of the current induced in the rotor, thus giving high starting torque with low starting current.

As the rotor gains in speed the frequency of the currents induced in it decreases and the relation between the currents in the two cages gradually and automatically changes to that shown for normal speed in fig. 16. For this speed the rotor currents are proportional to the slip, and they alternate at only about one cycle per second. At this low frequency the higher inductance of the inner cage winding is of relatively little importance and produces little choking effect.

The resistances of the two cages are now the chief limiting factor in the rotor currents. Consequently the inner, low-resistance cage carries by far the greater part of the total rotor current, with the advantageous results already mentioned. The starting torque of double squirrel cage motors is greater than that of the ordinary squirrel cage, but less than that of a motor with a single high resistance squirrel cage winding.

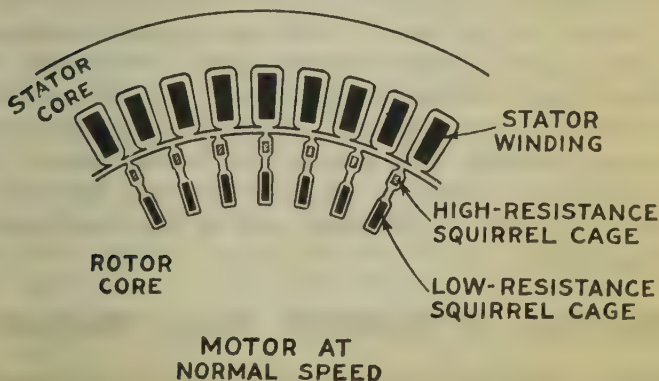


FIG. 16.—Section showing current relations in motor, fig. 15, when it has reached its full running speed. Now almost the only limit to the currents in the cage is resistance. It is because of the low resistance in the inner cage that its current is much higher than that of the high resistance cage. High efficiency, therefore, results during the operation.

Multi-Speed Squirrel Cage Motors.—In certain industrial applications where two, three or four different constant speeds are required, it is the usual practice to wind the stator with two or more separate independent windings, whose poles may be changed by changing the external connections, giving a limited number of different speeds.

The speeds so obtained are always in a constant ratio such as 1,800, 1,200, 900, 600, etc.

Multi-speed motors are classified or divided into three groups according to output as: *constant torque*, *constant horsepower*, or *variable torque*, and *horsepower*. The relations between torque, horsepower and speed is:

$$\text{Horsepower} = \frac{\text{Torque} \times \text{Speed}}{5,252}$$

Where torque is measured in foot-pound and speed in revolutions per minute.

The horsepower output of the constant torque type of motor varies directly as the speed. With the constant horsepower type the torque is inverse proportional to the speed, the horsepower being the same at each speed. In the case of the variable torque and horsepower type, both the horsepower and the torque decreases with a reduction in the speed. This latter type motor is usually employed on loads that vary as the square or cube of the speed, such as fans and blowers, centrifugal pumps, etc.

Starting of Squirrel Cage Motors

General.—The condition at the start of the motor is similar to that of a transformer with a short circuited secondary, since the rotor by construction is being short circuited by means of heavy metal bars as previously described.

When rated voltage is applied to the stator windings of a squirrel cage motor, a heavy current is drawn from the line, ranging from 4 to 7 times full load current, depending upon the type of motor.

This high current is momentary only and falls off rapidly as the motor increases its speed; its magnitude depends upon the electrical design of the motor and is independent of the mechanical load. The duration of the starting current, however, depends upon the time required for acceleration, which in turn, depends upon the nature of the driven load.

Starting of squirrel cage motors in industrial plants is usually accomplished by means of one of the following methods:

1. Directly across the line.
2. By auto-transformers (compensators).
3. By resistance in series with the stator winding.
4. By means of a step-down transformer.

Squirrel cage motors of 5 *h.p.* or less are generally started with line switches connecting them directly across the line. The switches are usually equipped with thermal devices which open the circuit when overloads are carried beyond predetermined limits. Large motors usually require various voltage reducing methods of the type previously mentioned.

All types of squirrel cage motors may be thrown directly across the line provided of course, that the starting currents do not cause voltage fluctuations interfering with power service elsewhere, and also that the starting currents do not exceed those permitted by local power regulations. When so started, a magnetic contactor is usually employed, operated from a start-stop push button, station or automatically from a float switch, thermostat, pressure regulator or other pilot circuit control device.

Across the Line Starting.—There are several across the line starting methods whose use depends upon the duty of the motor and the method of control desired. It is customary to employ a straight single throw switch or contactor for motors up to 5 *h.p.*, with fuses rated for the starting current.

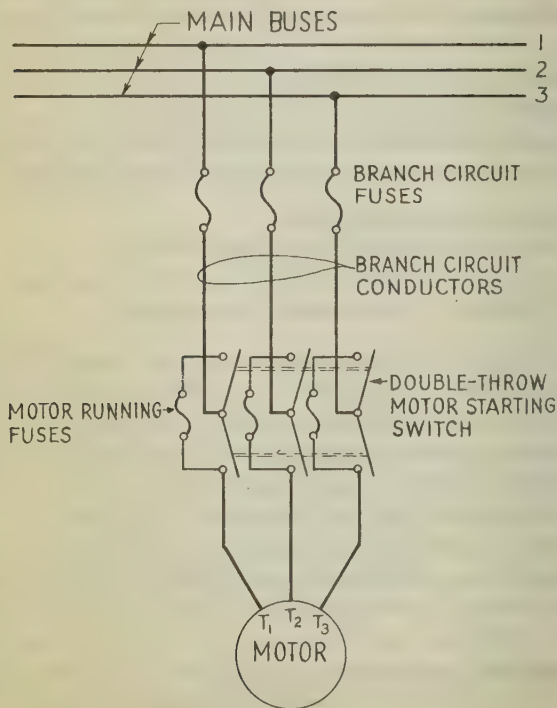
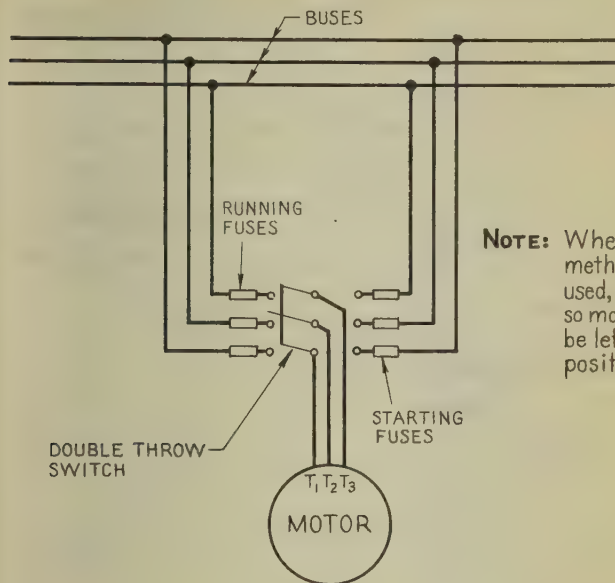


FIG. 17.—Across the line starting method employing a double throw switch. The switch is thrown in the lower position at starting, thus cutting out the running fuses. After the motor has attained its normal running speed, the switch is thrown to the upper position. To comply with the *National Electrical Code* requirements, the switch must be so constructed that it cannot be left in the starting (or lower) position.

The methods of starting, shown in figs. 17 and 18, require two sets of fuses and a double throw switch, the high current fuses being used for starting only, while the running fuses have a lower current rating.



NOTE: When a motor control method of this type be used, the switch must be so made that it cannot be left in the starting position.

FIG. 18.—Across the line starting arrangement with two sets of fuses—one set for starting and one set for running or normal operation.

The foregoing methods of starting are used for motors up to 250 volts.

With large motors having a voltage rating of from 440 to 600 volts, oil circuit breakers or magnetic switches are generally used. Both the oil circuit breaker and magnetic switches are provided with overload and under-voltage protection.

Various types of across-the-line starters used with squirrel cage motors are shown in figs. 19 to 22.

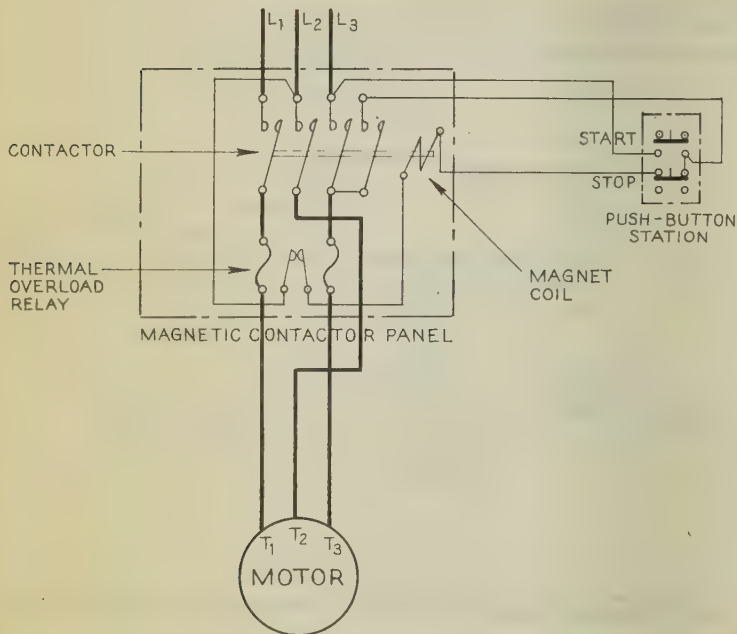


FIG. 19.—Typical across the line starting with remote control and thermal overload protection.
NOTE.—Only two thermal elements are needed. An overload or a break in the other phase (T_2) will force an increased current to flow through T_1 and T_3 , sufficient to actuate the relay.

Auto-Transformer Starting.—The auto-transformer or compensator method of starting employs two or three auto-transformers for the reduction of voltage to the motor terminal. The auto-transformer type of starter has the advantage of drawing less current from the line for a given reduction in voltage to the motor terminals.

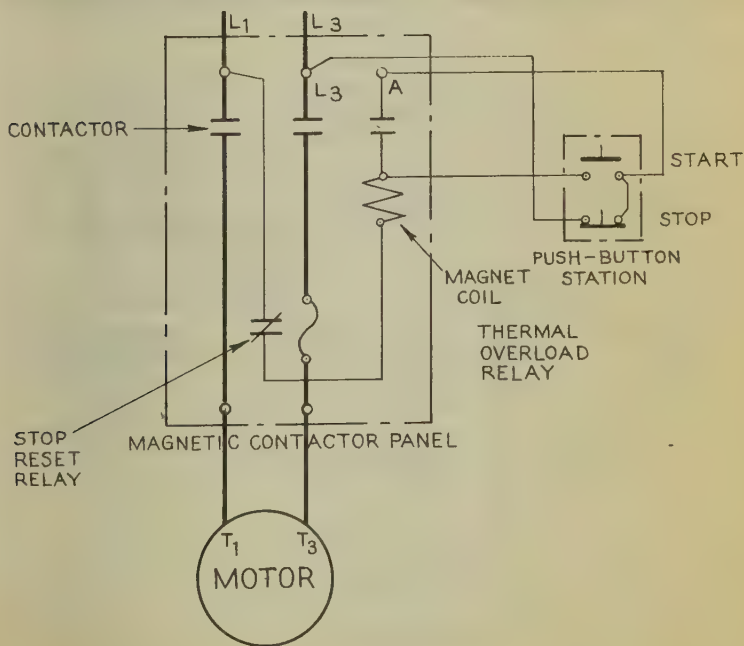


FIG. 20.—Wiring diagram for across the line starting method of a single phase motor. This starter includes an automatic start and stop push-button station in addition to a thermal overload relay.

This type of starter may employ oil circuit breakers or switches as illustrated in figs. 23 to 25.

With reference to fig. 24, the compensator consists of an auto-transformer, a manually-operated set of contacts, and a temperature overload relay. When the operating handle is pushed away from the operator, the autotransformer is connected to the power source, and at the same time, the motor which is being controlled is connected to taps in the auto-

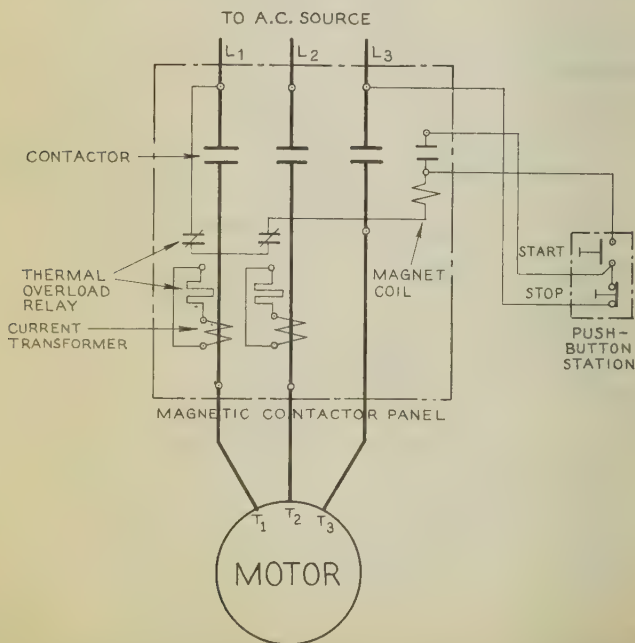


FIG. 21.—Typical magnetic starter for a three-phase motor. In this starter current transformers are employed in the heater circuits of the thermal overload relays.

transformer. These taps apply 50, 65 or 80% of line-voltage to the motor. This reduced voltage materially limits the torque on the motor in starting. In fact, the torque varies as the square of the applied voltage. If, for example, the 50% tap be used, the torque applied to the motor on starting will be 25% of the full-load torque; or if the 80% tap be used, the torque will be 64% of the full-voltage starting torque.

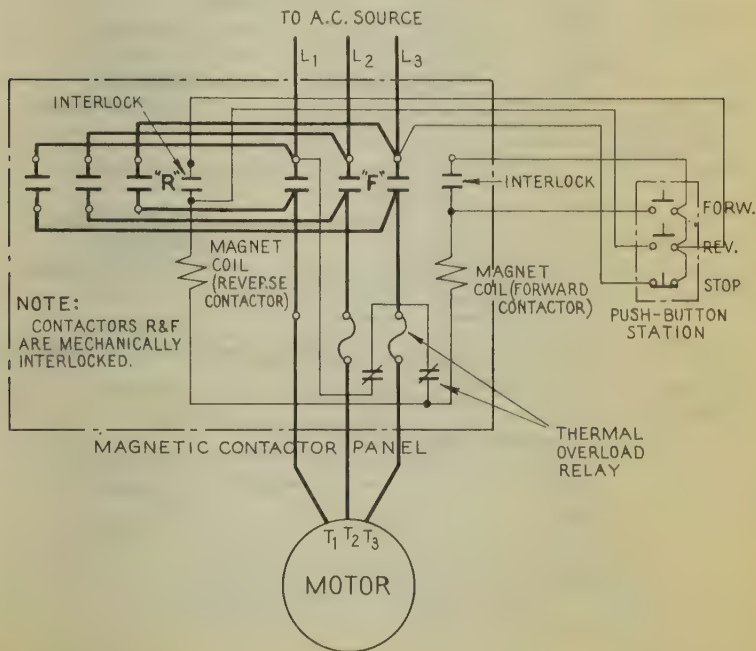


FIG. 22.—Connections for across the line reversing type starter. When the reverse button is being operated the magnet coil of the reverse contactor is energized. Because of the mechanical interlocking feature, the forward contactor drops out as the reverse contactor closes its contacts. With the reverse contactor closed, two phases leading to the motor are being interchanged, thus reversing the direction of rotation. The wiring includes the usual overload protection feature.

After the motor has accelerated, the operator quickly pulls the handle back to the running position, which connects the motor to full-line voltage. The handle is held in the running position by an under-voltage trip coil. If the overload relay trips out; if the line voltage fails momentarily; or if the cover be

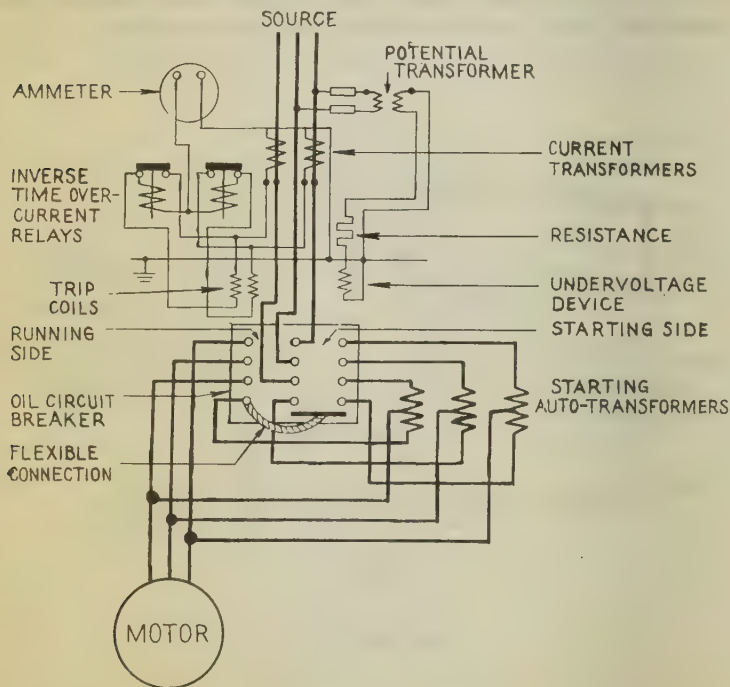


FIG. 23.—Connections for a double-throw motor starting oil circuit breaker with over-current protection, used in starting large squirrel cage motors. Where the motor is for heavy starting duty, the time over-current relay should be provided with a "quick-reset" valve. This is necessary because the starting current may cause the relay to function and without the quick reset feature, the contacts might not have time to reset themselves before the main breaker is closed, which would consequently be tripped out as soon as it was closed.

removed, the under-voltage coil is de-energized, and this allows the handle to return to the off position. To restart the motor, the overload relay must be reset by pushing a reset button on the outside of the case. Then the operating handle must be thrown first to the starting and next to the running position.

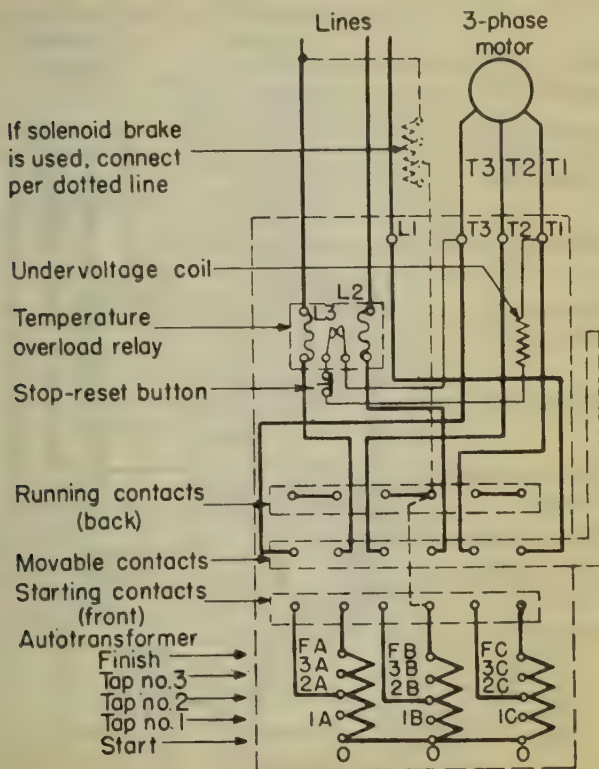


FIG. 24.—Connection diagram for autotransformer type, manual reduced voltage three-phase squirrel cage induction motor starter.

It is not possible to throw the handle from the off position directly to the running position (this would start the motor on full voltage), because the handle is so interlocked that it must first be pushed to the starting position before it can be pulled through the off position to the running position.

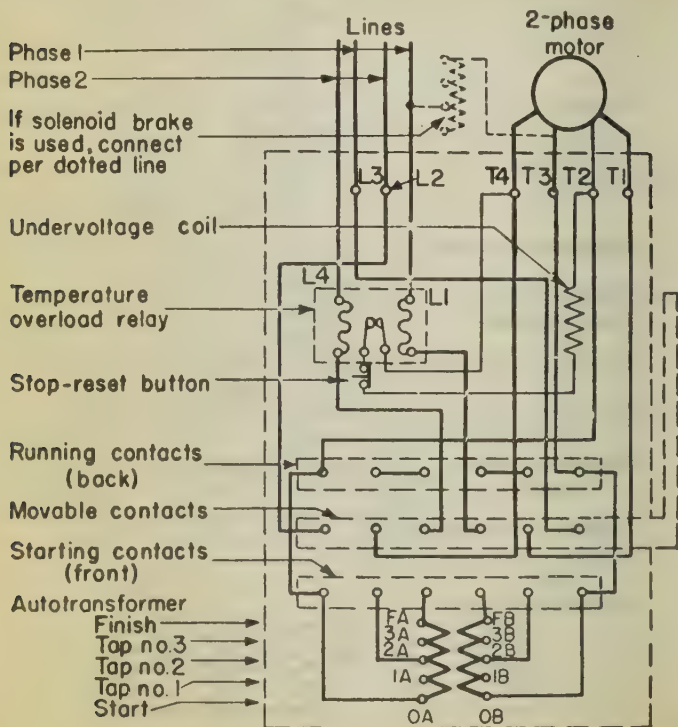


FIG. 25.—Connection diagram for autotransformer type manual reduced voltage, two-phase squirrel cage induction motor starter. The circuit arrangement and starting method is similar to that described for the three-phase motor.

Resistance Type Starting.—The resistance type starter, fig. 26, employs a heavy duty resistance in series with the line conductors. The drop of voltage through this resistance produces a reduced voltage at the motor terminals. The starting current of the motor is reduced in direct proportion to the reduction of the voltage applied to the motor terminals.

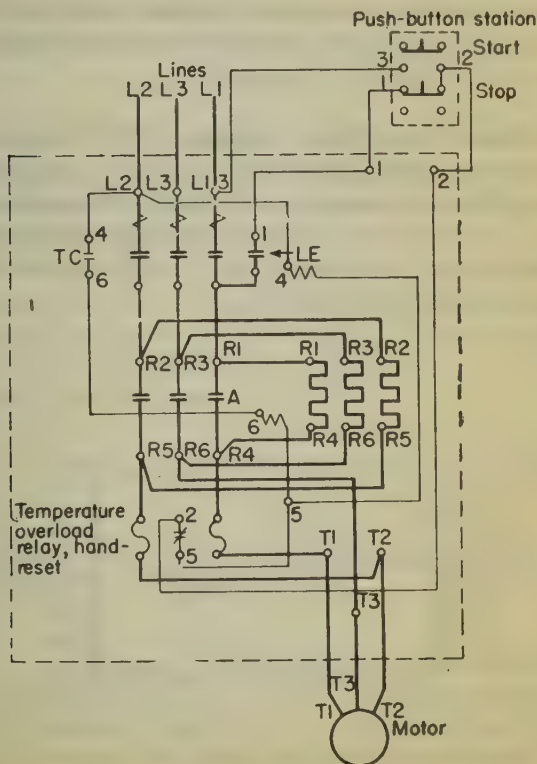


FIG. 26.—Connection diagram of a single step primary resistor type automatic starter for squirrel cage induction motor. In the diagram LE represents the line contactor; A, accelerating contactor; TC, time closing contact.

It should be noted, however, that while in the case of a resistance starter being used to reduce the voltage to half value, for example, the current drawn from the line will also be half of the full voltage value, whereas, if an auto-transformer starter be used, the current drawn from the line varies as the square of the voltage ratio of the transformer. Thus, if half voltage be applied to the motor terminal from the secondary of the auto-transformer, the current drawn from the line will only be one-fourth the full voltage value.

Step-Down Transformer Starting.—The voltage step-down transformer method of starting is but rarely used on account of its higher cost as compared with that of the auto-transformer method. A step-down voltage transformer consists of two complete coils or windings while an auto-transformer requires but one tapped coil or winding.

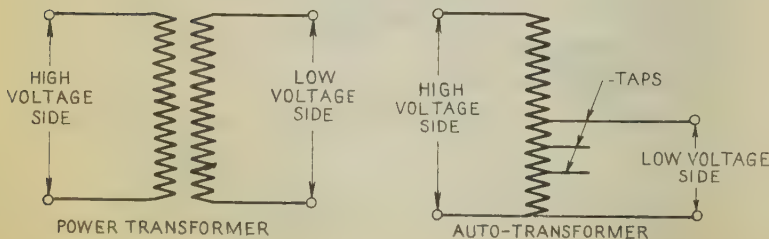


FIG. 27.—Diagram illustrating comparison in copper requirements between a single-phase power transformer unit and similar autotransformer for motor starting.

Full Load Current Calculations.—If the power factor and efficiency of a three-phase motor be known, its full load current may be found from the formula:

$$I = \frac{\text{Horsepower rating} \times 746}{\sqrt{3} \times \text{Power factor} \times \text{Efficiency} \times \text{Voltage}}$$

Where power factor and efficiency are expressed as decimals, for a two-phase motor the full load current similarly is:

$$I = \frac{\text{Horsepower rating} \times 746}{\sqrt{2} \times \text{Power factor} \times \text{Efficiency} \times \text{Voltage}}$$

Where two-phase motors are supplied from a three-wire circuit, the current in the common wire is the $\sqrt{2}$ times the current in the other two wires.

Example.—*A three-phase squirrel cage 600 volt induction motor is known to deliver 250 h.p. at the pulley. If the power factor and efficiency are .93 and 93%, respectively, what current does the motor draw from the line?*

Solution.—A substitution of values in the previously given formula gives:

$$I = \frac{250 \times 746}{\sqrt{3} \times 0.93 \times 0.93 \times 600} = 208 \text{ amperes (approx.)}$$

Control Equipment

General.—Selecting the right squirrel cage motor for the machine in question is but one step towards meeting the motor application problem. Selection of the proper control apparatus is just as important as the selection of the motor itself. The

intelligent choice of motor control involves a complete knowledge of types of control apparatus available, and their functions.

The functions of control apparatus for squirrel cage motors are:

1. Starting the motor on (a) full voltage, or (b) reduced voltage. (See pages 304 to 314.)
2. Stopping the motor.
3. Disconnecting the motor upon failure of voltage.
4. Limiting the motor load.
5. Changing the direction of rotation of the rotor.
6. Starting and stopping the motor (a) at fixed points in a given cycle of operation, (b) at the limit of travel of the load, or (c) when selected temperature or pressures are reached.

Where multi-speed motors are involved, the following functions may be added:

7. Changing the speed of rotation (*r.p.m.*).
8. Starting the motor with a definite speed sequence.

Stopping the Motor.—Control devices permit motors to be stopped as follows:

1. Under the direction of an operator.
2. Under the control of a pilot circuit device such as thermostat, pressure regulator, float switch, limit or cam switch.
3. Under the control of protective devices which will disconnect the motor under overload conditions detrimental to the motor, or upon failure of voltage or lost phase.

Protecting the Motor.—To protect motors against injury during severe momentary or sustained overloads, over-current devices are employed to disconnect them from the line. These devices are of two general types:

1. Thermal overload relay.
2. Dashpot overload relay.

The characteristics of the thermal type overload relay is illustrated in fig. 28, which indicates an inverse relationship between current and time, that is, the greater the current, the sooner the relay operates to disconnect the motor from the line.* When the relay operates, it opens an independent, or pilot circuit, which causes the main line contacts to drop out, thus disconnecting the motor from the line. Dashpot overload relays have a similar inverse time-current relationship. Thermal and dashpot overload relays are of two types:

1. Hand reset.
2. Automatic reset.

As the names denote, the hand reset type must be reset by hand after having tripped (usually by pressing a button projecting through the enclosing case) whereas the automatic reset type resets themselves automatically.

Dashpot overload relays are generally of the automatic reset type, but they can be made of the hand reset type by providing a hand reset attachment which will prevent automatic resetting.

Standard polyphase motor control devices almost without exception are equipped with two thermal overload relays of the hand reset type. Thermal overload relays of the automatic reset type are also used.

*NOTE.—Properly selected (or adjusted) overload relays operate to disconnect the motor from the line when the temperature of the motor windings approaches the danger temperature of cotton insulation.

The purpose of the relays is to prevent burn-outs of motor windings; hence, they should be selected carefully to accomplish that end. Thermal relays must be of the proper rating, and dashpot relays must be properly set to disconnect motors from the line before operating conditions tax the motor windings to the point of breakdown.

Overload relays protect polyphase motors against phase failure due to a blown fuse or some other power interruption in one line of the supply circuit. If phase failure occurs while

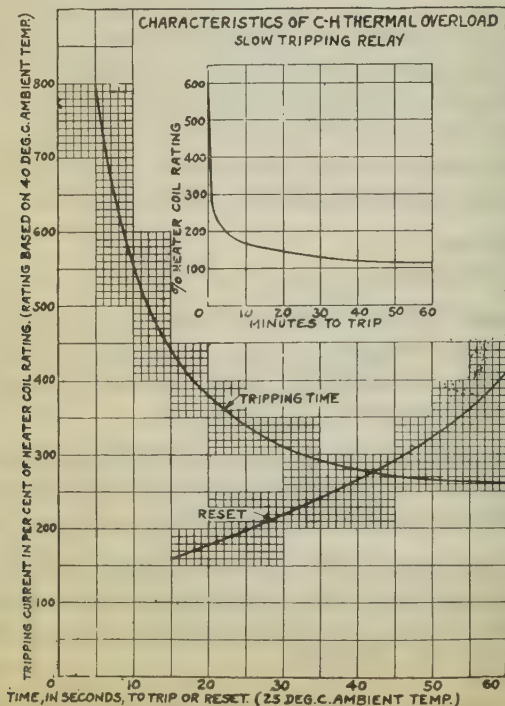


FIG. 28.—Curves showing thermal overload relay characteristics.

the motor is at rest, the motor will trip the overload relay, thereby disconnecting the motor from the line.

If phase failure occurs while the motor is running, the motor will continue to run provided the load is not too great. The current taken by the motor when running single phase will be from two or three times the normal three-phase value, and unless the motor be very lightly loaded, will be sufficient to trip the overload relays before the motor windings can be damaged. If the load be very light, the overload relays will not trip, and the motor will continue to operate without damage until shut down, but will refuse to start the next time an attempt is made to operate it.

After hand reset overload relays have tripped, they must be manually reset by an operator before the control will again connect the motor to the line. The operator, noting the failure of the motor to start, will presumably investigate and remove the trouble.

Automatic reset overload relays in magnetic starters controlled by two-wire pilot circuit devices, such as float switches, pressure regulators, thermostats, snap switches, etc., will cause the motor to be connected to the line again and again, and each time a heavy load current will be drawn from the line which will reheat the motor windings until they burn out.

Voltage failure also requires protection to operators and motors. Control apparatus designed so that the main line contacts are held in by a magnet coil operated across one phase of the supply circuit, can have their control or pilot circuits so arranged that upon failure of voltage, the motor will not restart† until the operator goes through the necessary

†NOTE.—When control is so arranged, *low voltage protection* is said to be provided, which is defined as follows: "Low voltage protection is the effect of a device operative on the reduction or failure of voltage, to cause and maintain the interruption of power to the main circuit." For wiring diagram see page 160.

starting operations. Three-wire pilot circuit control is required for such control devices "to cause and maintain the interruption of power to the main circuit." Motor applications involving control apparatus which starts and stops the motor automatically, by means of two-wire pilot circuit devices, such as thermostats, float switches, and pressure regulators, can not be arranged for low voltage protection. Automatic control devices operated by such pilot circuit devices will operate in such a manner as to disconnect the motor from the line upon failure or reduction in voltage, but will reconnect the motor to the line upon return of voltage.†

Starting and Stopping Motor at Predetermined Conditions.—Over-traveling of a driven load is prevented by operating magnetically-operated control devices in conjunction with cam switches, limit switches, etc., the motor being automatically disconnected from the line when a cam or limit switch is operated.

Reversing Motors.—To reverse squirrel-cage motors, it is but necessary to interchange two leads—(a) any two leads to three-phase motors; (b) two leads of either phase to two-phase four-wire motors, leaving one phase intact; (c) the two outside leads to two-phase three-wire motors, leaving the common lead intact. Reversal is accomplished by means of either a small drum controller (for small motors) or reversing magnetic contactors (for larger motors).

†NOTE.—When control is so arranged, *low voltage release* is said to be provided, which is defined as follows: "Under-voltage is the effect of a device, operative on the reduction or failure of voltage to cause the interruption of power to the main circuit, but not to prevent the reestablishment of the main circuit on return of voltage." For wiring diagram see page 161.

Control Equipment for Multi-Speed Motors.—Multi-speed motors involve all the devices heretofore mentioned to effect starting and stopping under the six conditions listed. Additional control devices are required, however, for changing their speeds, which is accomplished by regrouping the motor windings. Two types of controls are used:

1. Manually-operated speed setting drums, and
2. Combinations of magnetic contactors.

Magnetically-operated controllers can be so arranged that the multi-speed motors will always start up through low speed, subsequently being transferred to a higher operating speed. The auxiliary control device accomplishing this is known as a compelling relay which may be operated either manually or automatically by means of a time-delay device.

Application of Squirrel Cage Motors

General.—As pointed out in the beginning of this chapter, the squirrel cage motor on account of its simplicity of construction, together with the fact that it can be built with electrical characteristics to suit almost any industrial requirement, has made this one of the most widely used machines.

As noted from the characteristics and classification, squirrel cage motors as a rule are not suitable where a high starting torque is required, but are most suitable where the starting torque requirements are of a medium or low value.

In selecting a motor for a certain application, there are in addition to torque and starting current considerations, a large number of factors effecting an economical and efficient operation.

The selection is determined in whole or in part by the user on the basis of available data such as speed range and regulation, mechanical arrangement, available voltage, direction of rota-

tion and reversing, operating schedule, method of control, surrounding atmospheres, etc.

Since the power factor and efficiency of any induction motor is lower at light loads than at high loads, it is obvious that in selecting a motor for a definite load, the size should be such as to permit the operation of the motor as nearly as possible at full load.

Also low speed motors have a lower power factor and weigh more per horsepower than high speed motors. Therefore, in choosing a motor for a certain duty, size and speed should be carefully considered so as to give the most economical and satisfactory service.

For the largest group of applications as represented by fans, pumps, compressors, conveyors, etc., which are started and stopped infrequently and have low inertia loads so that the motor can accelerate in a few seconds, the conventional general purpose *NEMA Class A* motor can be used.

If a motor be installed in a location where there is limitation on the starting current, the modified general purpose motor *NEMA Class B* can be used, or if the starting current be still in excess of what can be permitted, then reduced voltage starting is employed.

On those applications where reduced voltage starting does not give sufficient torque to start the load with either *NEMA Class A* or *B* motor, *Class C* motor with its high inherent torque along with the reduced starting current supplied with reduced voltage starting may be used.

Conveyors and Compressors.—On these applications which sometimes require a starting torque of at least twice full load, motor torque *NEMA Class C* motor may be used with full-load voltage starting.

Large Fans.—This type of drive is one which requires special consideration. These drives, once they are accelerated, run continuously at full load and, therefore, it is desirable to have the best possible efficiency and power factor. Some of the fans, however, have extremely high values of moment of inertia* (WR^2) and motors with normal starting torque characteristics may require from 30 seconds to 1 minute to accelerate. With starting current flowing in both the rotor and stator for this long period of time, it may generate sufficient heat to damage the winding either in the form of a charred insulation on the primaries. What is more probable, the rotor winding will get so hot that the bars and rings will warp and bend and eventually crack and break.

To meet this application with a squirrel cage motor special *NEMA Class B* motor is used to reduce the starting current to a minimum and then the rotor of the motor is designed with a large mass of material especially in the end rings so that it is possible for the motor rotor to absorb the tremendous losses during the accelerating period without reaching excessive temperatures. Once the motor reaches its full load speed the losses return to normal and the rotor rapidly cools down to its normal operating temperatures.

Flywheels, Presses and Bolt-headers.—Another continuous running motor application which requires special consideration is on drives where there is high external inertia quite often in the form of a flywheel and where the load instead of being of a continuous full load torque is pulsating in nature. Typical examples of this type of application are *presses* and *bolt headers*. In this type of application no work is being done for the majority of time and then a peak load occurs which may require torques many times the full load torque of the motor.

*NOTE.—For a detailed treatment of methods for determination of WR^2 as related to motor drives, see pages 328 to 336.

Under these conditions the running efficiency of the motor at full load is not important because it never operates at that point and, therefore, the motor is deliberately designed with more than normal secondary resistance so that it has a tendency to slow down as the load comes on the drive. This tendency for the motor to slow down permits the flywheel to give up energy to absorb the peak load with the motor exerting no more than full load torque. However, the energy that is taken out of the flywheel during the work stroke must be returned to it by the motor and, therefore, the motor must have sufficient torque to accelerate the flywheel before the next work stroke is made.

Since presses work at widely varying rates, say from 2 or 3 work strokes per minute to as high as 100 to 150 work strokes per minute, the correct amount of rotor resistance will vary, depending upon the number of strokes per minute made. On the extremely large presses making only a few strokes per minute, there is ample time for the flywheel to slow down 10 to 15% during the work stroke and give up a considerable part of its kinetic energy. Therefore, motors used on this type of press should have high slip, and one of the standard ratings listed by the motor manufacturers is a motor having 8 to 13% slip, and is the correct motor to use.

As the number of strokes per minute increase, the length of time of the working stroke decrease, and there is not much time available for the flywheel to slow down, nor is there much time for the motor to re-accelerate the flywheel between strokes, so that the amount of slow-down of the flywheel is usually between 5 and 10%, and the standard line of press motors with 5 to 8% slip has been designed for this application. These presses usually make in the neighborhood of 10 to 40 strokes per minute.

On the smaller presses making 100 to 150 strokes per minute, there is very little time for the flywheel to accelerate or deceler-

ate, and the standard motor which has approximately 3% slip is entirely adequate for the application and there is no object in supplying the high slip motor. Quite often someone tries to use *NEMA Class C* motors on these high torque applications, and if they do not have trouble due to overheating, trouble may develop in the form of mechanical failure of the rotor due to the unequal heating in the double deck winding as previously explained.

Frequent Starting and Stopping Machines.—These special applications just described are fairly simple so far as applying the proper motor is concerned, and rather accurate calculations can be made to determine the motor heating and thus apply the proper motor. However, there is another group of applications which involves frequent starting and stopping or reversing which may or may not involve variable running loads and even periods when the motor is at rest. These applications are much more difficult to calculate and also it is usually hard to get a set of fixed operating conditions. Typical applications of this type have external WR^2 's that are roughly comparable to the WR^2 of the motor rotor itself, and in fact in most cases every attempt is made by the machinery builder to reduce the inertia of the revolving parts, since it is obvious that the heating of the motor is directly proportional to the inertia of the drive. Some applications require 40 to 50 reversals per minute and 10 to 15 reversals per minute are common.

Motor Losses.—No attempt will be made here to set up methods for calculating the losses on a given duty cycle, but merely to point out some of the factors that determine the design of the proper motor for the application. In the first place the losses in the motor for a drive of this type can be

divided into two parts, namely, the *losses during changes in speed*, and the *running losses*. Unfortunately, an increase in rotor resistance which tends to reduce the motor losses for changes in speed, tends to increase the losses while running at constant speed. If the size of the motor has been determined by the torque required to give rapid acceleration and deceleration and has a very light running load, then the running losses can be largely ignored. If on the other hand the motor must carry full load torque after it has accelerated to full speed, then it is important to keep the slip to a minimum amount.

Rotor Design.—As previously mentioned, it is also important to keep both the WR^2 of the motor and the load to a minimum. After the machinery builder has designed his machine to reduce this value to a minimum, then it is up to the motor manufacturer to proportion the rotor to keep the motor WR^2 to a minimum. Even though squirrel cage motors are compact in design and small for the horse power rating delivered, the inertia of the rotor can often be reduced as much as 50% by changing the ratio of rotor diameter and length from what is used on general purpose motors.

Running Tests.—Quite often it is only by running tests on the actual machine that the best balance of these various factors can be determined, and this procedure is often followed. While this expense and trouble is not justified for a single application, it is very desirable to do so in case a special motor is being designed for a machine that is going to be produced in quantities.

Drilling and tapping machines, turret lathes, extractors, washers, etc., are all examples of where this procedure is quite often followed.

Although it is not within the scope of this chapter to discuss the various mechanical modifications that are often required on squirrel cage motors, it is desirable to consider the ventilation of the motors and the type of insulation used. We all know that it is quite often desirable to build the motor into the machine or to make the motor totally enclosed to protect it from cast-iron dust, oil fumes or other dirt in the atmosphere surrounding the motor. These enclosures restrict the ventilation of the motor and reduce the amount of heat that can be dissipated by the motor. Even with the motor ideally designed for the application, the losses on duty cycle operation are usually higher than for a motor operating continuously at a constant load. The amount of losses that can be dissipated by a motor with a given temperature rise is usually roughly proportional to the radiating surface of the motor when it is totally enclosed or in proportion to the amount of air circulated through it when of the open type.

When it is satisfactory to supply an open motor, the temperature rise of the motor can be kept down by supplying a more elaborate blower mechanism on the rotor than normally supplied which tends to circulate a much larger volume of air and thus keep down the temperature. However, care must be exercised that this additional rotor does not materially increase the WR^2 of the unit. Of course, the size of the motor can always be increased and, therefore, dissipate more losses, but this is undesirable from a space standpoint and also the size must be increased in such a manner that the rotor WR^2 is not increased to gain much advantage.

On many severe duty cycle jobs it is found that even with the best possible electrical design the losses are sufficient to cause temperature rises in the motor higher than can be withstood by normal *Class A insulation*, and in these cases the

answer is high temperature insulation. For many years *Class B insulation* has been recognized as a standard type of insulation for motors, and it permits the motor to operate at a 75°C. rise instead of a 40 to 55° rise. *Class B insulation* makes use of the best insulating materials that are available, such as asbestos, mica and glass. However, it is used only where necessary due to a considerable increase in cost of the motor so equipped.

Determination of Moment of Inertia

Definition.—Moment of inertia may be defined as the integral sum of the products of each indefinitely small portions of mass or area into the square of its distance from a given axis. It is a measure of the effectiveness of mass in rotation. In the rotation of a rigid body not only the body's mass, but the distribution of the mass about the axis of rotation determines the change in the angular velocity resulting from the action of a given torque for a given time.

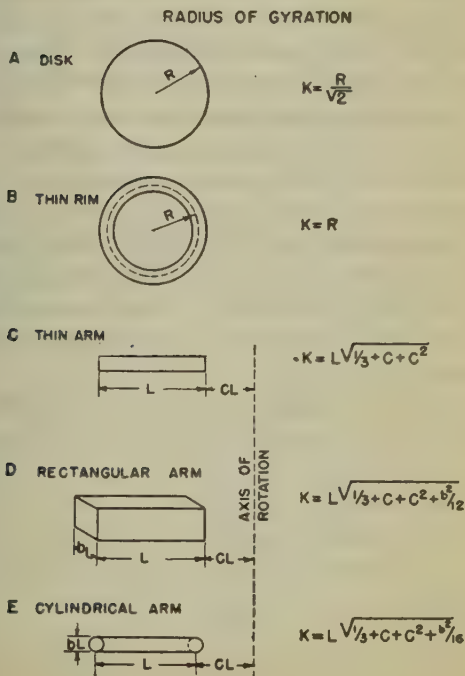
The moment of inertia of a driven load is of extreme importance in the proper selection of a motor for those cases where the motor accelerates a heavy load or makes frequent starts. Outstanding examples are motors for rapid reversing service, extractors, large fans, etc.

Determination of the moment of inertia is not difficult, but is often neglected because of the lack of familiarity with a suitable method.

In engineering work, the moment of inertia is expressed as WR^2 in terms of pound-feet squared. These units are commensurate with the other engineering units of pounds, feet, horsepower, etc.

According to *General Electric Company's Engineers*, WR^2 can be determined in three ways, namely:

1. By calculation (that need not be too precise to be useful).
2. By measured comparison with an easily computed object.
3. By direct measurement.



FIGS. 29 to 33.—Showing radius of gyration (K) in inches for five basic components.

Calculation of WR^2 .—The moment of inertia WR^2 is the product of the weight of an object and the square of the radius of gyration, that is, $WR^2 = Wk^2$, where W is the weight of the object in pounds and k is the radius of gyration in feet which, in turn, could be considered an average of the radii from the axis of rotation of each infinitesimal part of the object. The calculation of a relatively complicated object can readily be made by breaking it up into its simple components, easy to calculate in themselves. Most rotating objects can be broken down to a series of rims, spokes, and discs. Since the WR^2 of the segregated parts add directly to give the WR^2 of the whole, provided a common axis be considered in all cases, each part can be considered in its simplest geometric form.

Figs. 29 to 33 show the five basic components and their radii of gyration k in inches. Fig. 34 shows the WR^2 of discs, which can be used to determine the WR^2 of thick rims by subtracting the WR^2 of an imaginary disc of the inside diameter from that of a disc of the outside diameter. The common *engineering handbooks* have many formulas for complicated objects which may prove useful.

As an example, the calculation of the WR^2 of the flywheel in fig. 35 is shown. The computation is best carried on in tabular form:

Part	Volume (Cu. In.)	Weight (Lb.)	K (In.)	WR^2 (Lb.-In. Squared)
Rim	415	106	11	12,800
6 Spokes	103	26	6.2	1,000
Hub	21	5	1.0	5
				13,805

$$WR^2 \text{ (lb.-ft. squared)} = \frac{13,805}{144} = 95.9$$

It can be noted that the major part is in the rim and that only this need be calculated, even for a fairly close approximation.

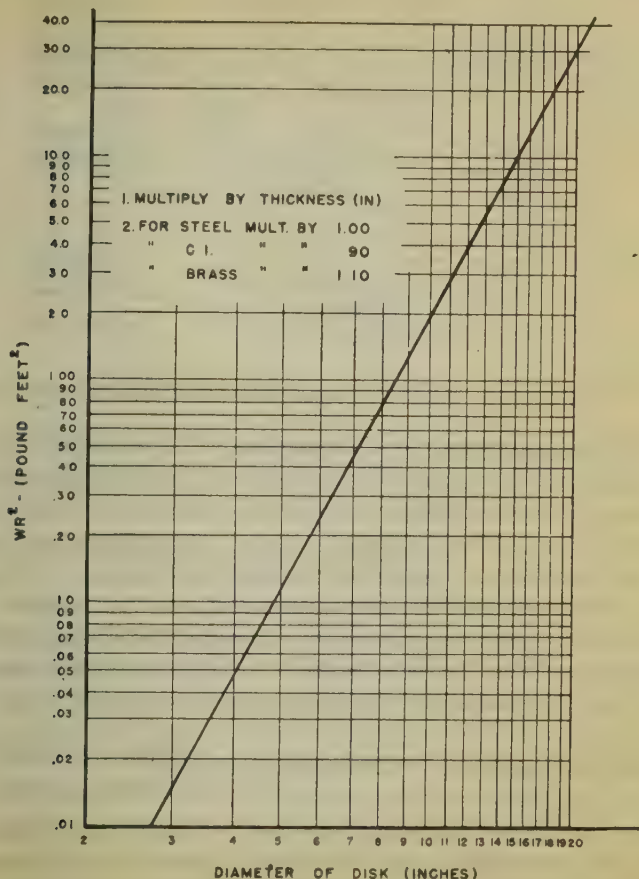


FIG. 34.—Chart giving values for graphic determination of WR^2 when diameter of disc and its thickness and material be known.

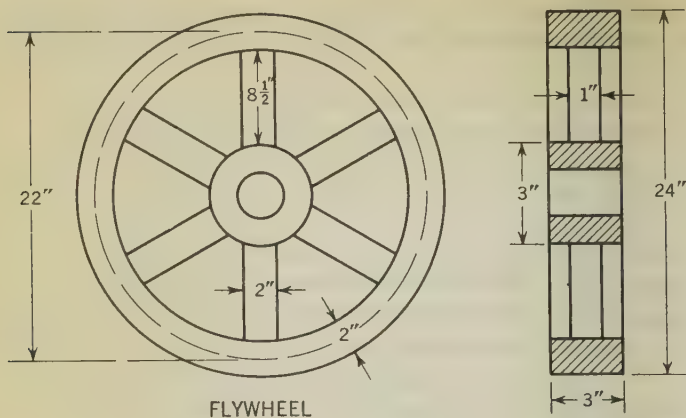


FIG. 35.—Showing necessary dimensions of typical flywheel in order to determine its WR^2 .

WR^2 Measurement by Comparison.—This method consists of suspending the object to be measured from a wire with its axis of rotation coinciding as nearly as possible with the axis or center of the platform, giving it a twist, and taking the time for a given number of complete torsional oscillations. A disc of about the same WR^2 is then suspended, also in balance, from the same wire and the time of the same number of oscillations is measured. The WR^2 of the disc is calculated, say from the chart and the value for the tested object computed from:

$$WR^2 \text{ (unknown)} = WR^2 \text{ (known)} \times \left(\frac{\text{Time of unknown}}{\text{Time of known}} \right)^2$$

Fig. 36 shows the general method. Care must be taken to have the wire long enough to make the time of each oscillation convenient to measure, and to twist the object in such a manner that it rotates about the support as its center. It is also im-

portant that the wire be firmly fixed at both ends, so that it will not move in the supports, and so that it does not bend at the supports.

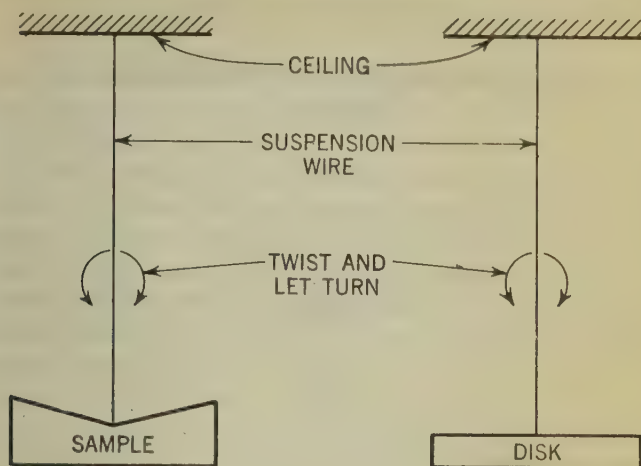


FIG. 36.—Showing measurement of WR^2 by comparison.

Direct Measurement of WR^2 .—This method consists of setting up the object as a torsional pendulum, measuring (1) its time of oscillation; (2) its weight; (3) the dimensions of the supporting means, and (4) computing the WR^2 . Fig. 37 shows the general arrangement. This method is perhaps the easiest to use in the field, as any wire, rope, string or chain can be used as supports, if it be fairly flexible and light compared to the weight of the object. A ruler, a watch, and a set of scales are all that are necessary to take the measurements. If the object be not easily “hooked onto” a light platform can be

suspended and its WR^2 determined. The object is then placed on the platform with its axis of rotation coinciding as nearly as possible with the axis or center of the platform, and the total WR^2 measured. The value for the unknown is found by subtracting that of the platform from the total.

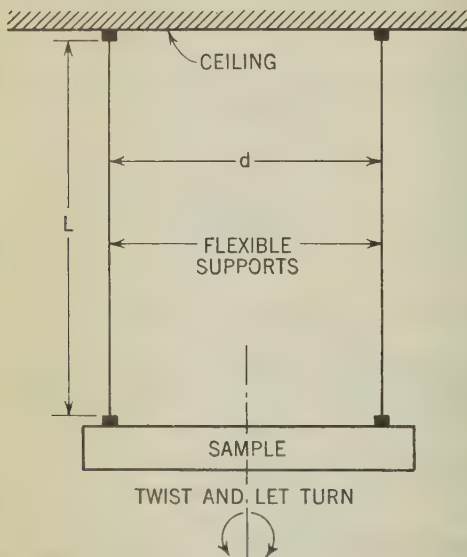


FIG. 37.—Showing direct measurement of WR^2 .

The time t is the time for any convenient number of complete oscillations N . A complete oscillation is the movement of the object from some one position back to the same position and traveling in the same direction. The computation is made from the formula:

$$WR^2 = \frac{0.016 W d^2 t^2}{L N^2} \text{ (pound-feet squared)}$$

Where W = weight of object in pounds.

d = distance between supports in inches.

L = strength of supports in inches (should be at least 4 ft.).

t = time in seconds for N oscillations.

Since the location of the decimal point is often confusing, it is sometimes wise to make a rough calculation by the curve, fig. 34 as a check.

The effectiveness of WR^2 depends upon the speed at which it rotates. Hence, in any mechanical system with shafts running at different speeds, the WR^2 must be referred to some one shaft. For motor work, the motor shaft and motor speed are usually used as the basis of comparison. In any event, it is always necessary to state clearly to what shaft it is referred, for example "flywheel WR^2 referred to motor shaft." The formula for conversion is:

$$WR^2 \text{ (referred to shaft } A) = WR^2 \text{ (referred to shaft } B) \times \left(\frac{r.p.m. \text{ of } B}{r.p.m. \text{ of } A} \right)^2$$

Masses that are part of the system and that move in straight lines, must also be reduced to the reference shaft. The equivalent WR^2 of the lineally moving mass is:

$$WR^2 = \frac{WV^2}{(2\pi N)^2}$$

Where W = weight of lineally moving part in pounds.

V = velocity in *f.p.m.*

N = *r.p.m.* of reference shaft.

For example, the equivalent WR^2 of the simple hoist shown in fig. 38 can be calculated as follows:

$$WR^2 \text{ of sheave referred to motor shaft} = 18 \left(\frac{600}{1800} \right)^2 = 2.00$$

$$WR^2 \text{ of cable on sheave referred to motor shaft} = 14 \times 1 \times \left(\frac{13}{2 \times 12} \right)^2 \times \left(\frac{600}{1800} \right)^2 = 0.45$$

$$WR^2 \text{ of cable and weight (velocity} = 2,040 f.p.m.) = (15 + 10 \times 1) \left(\frac{2040}{2\pi \times 1800} \right)^2 = 0.82$$

$$\text{Total equivalent of } WR^2 \text{ of system} = 3.27 \text{ lb.-ft.}^2$$

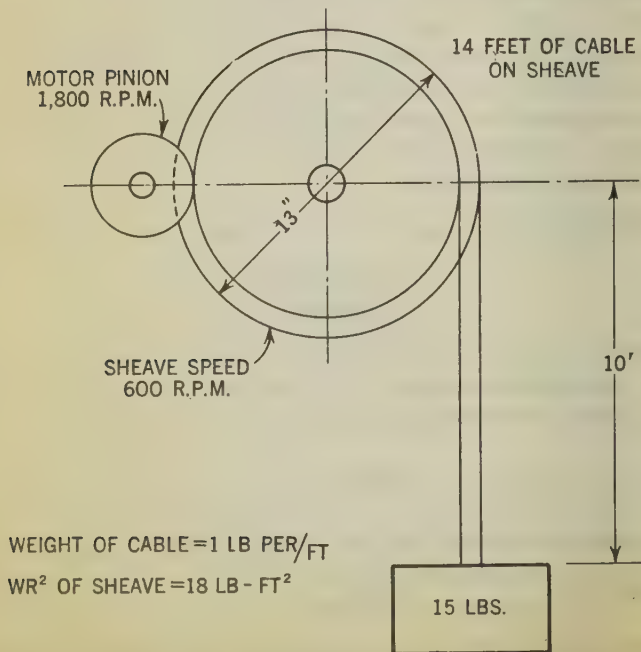


FIG. 38.—Illustrating a simple hoist with necessary data for determination of WR^2 in system.

CHAPTER 10

The Wound Rotor Motor

(Slip Ring Motor)

Principal Difference between the Squirrel Cage and Wound Rotor Induction Motor.—Insofar as the stator is concerned, the squirrel cage motor and the wound rotor motor are identical. The outstanding difference between the two motors lies in the rotor winding.

In squirrel cage motors previously described, the rotor winding is practically self contained, and is not connected either mechanically or electrically with the outside power supply or control circuit. It consists of a number of straight bars uniformly distributed around the periphery of the rotor and short circuited at both ends by end rings to which they are integrally joined. Since the rotor bars and end rings have fixed resistances, such characteristics as starting and pull-out torques, rate of acceleration, and full load operating speed cannot be changed for a given motor installation.

In wound rotor motors, on the other hand, the rotor winding consists of insulated coils of wire not permanently short circuited as in the case of the squirrel cage rotors, but connected in regular succession to form a definite polar area having the same number of poles as the stator. The ends of these rotor windings are brought out to collector rings or *slip rings* as they are commonly termed.

The currents induced in the rotor are carried by means of slip rings (and a number of carbon brushes riding on the slip rings) to an externally mounted resistance which can be regulated at will by special control as indicated in fig. 1.

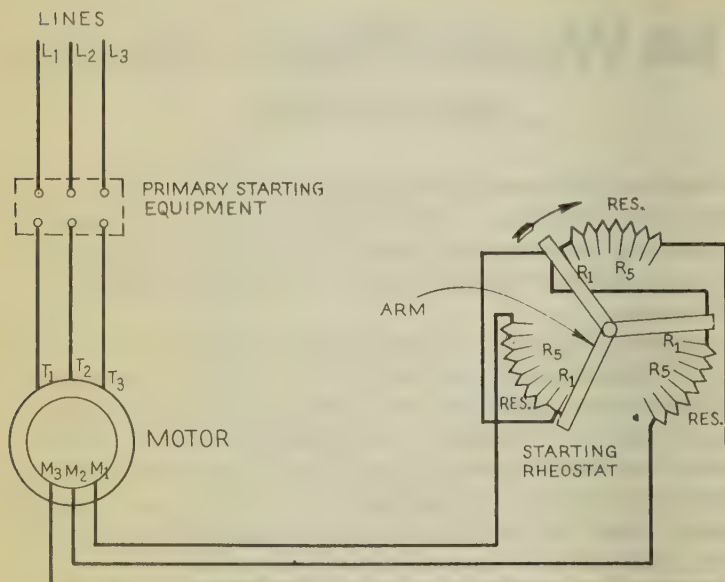


FIG. 1.—Schematic diagram of a starter or controller for a wound rotor induction motor. The resistances in the three phases of the rotor are gradually cut out to increase the speed of the motor. Speed regulators of this type are usually designed in sizes of up to 40 h.p., and for rotor currents of approximately 100 amp.

By varying the amount of resistance in the rotor circuit a corresponding variation in the motor characteristics can be obtained. Thus, by inserting a high external resistance in the rotor circuit at starting, a high starting torque can be developed with a low starting current.

As the motor accelerates up to speed the resistance is gradually cut out until at full speed the resistance is entirely cut out and the rotor windings are short circuited.

Wound Rotor Motor Characteristics.—By varying the values of the resistance in the rotor circuit the characteristics of the motor will be affected as follows:

1. Variation in the starting torque and current.
2. Smooth acceleration.
3. Variation in operating speed.

The operating speed depends, of course, entirely upon the amount of resistance incorporated in the control equipment.

Fig. 2 shows the speed torque and corresponding speed-current curves obtainable in a typical wound rotor induction motor using different values of external rotor resistance. The numbers given on the curves indicate the rotor circuit resistance in per cent of the value required to give full-load torque at standstill.

The curves, fig. 2, illustrate that external resistance in the rotor circuit reduces the speed at which the rotor will operate with a given load torque. If the rotor resistor be designed for continuous duty a portion of it may be allowed to remain in the circuit, thus obtaining reduced speed operation. Thus, the motor has a varying speed characteristic; that is, any change in load results in a considerable change in speed.

It should be borne in mind, however, that the efficiency of a wound rotor motor, including the (I^2R) losses in the rotor resistance, is reduced in direct proportion to the speed reduction obtained.

Thus, the wound rotor motor has found its use in cranes, hoists and elevators which are operated intermittently and not over long periods, where exact speed regulation and loss in efficiency are of little consequence. If, however, lower speed is required over longer periods, poor speed regulation and loss in efficiency may become prohibitive.

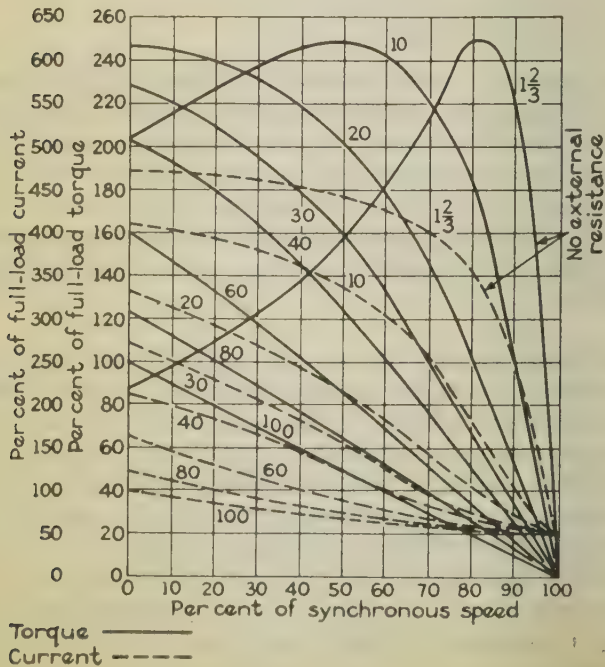


FIG. 2.—Typical speed-torque and speed-current curves of wound rotor induction motor.

Control Equipment

From the foregoing it has been found that the wound rotor motors have certain inherent speed-torque characteristics and that these can be considerably altered by the secondary control equipment which introduces into the rotor circuit varying value of resistance.

Since the control equipment has this ability a further study of the most common type of controllers and associated equipment is appropriate.

The function of controllers used with wound rotor motors are:

1. To start the motor without damage or undue disturbance to motor, driven machine, or power supply.
2. To stop the motor in a satisfactory manner.
3. To reverse the motor.
4. To run the motor at one or more predetermined speed below synchronous.
5. To handle an overhauling load satisfactorily.
6. To protect the motor.

The various types of controllers utilized may be divided into the following groups, depending upon the size and function of the motor, as:

1. Face plate starters.
2. Face plate speed regulators.
3. Multi-switch starters.
4. Drum controllers.
5. Motor-driven drum controllers.
6. Magnetic starters, etc.

Simple Face Plate Starter.—A typical wiring diagram of a secondary resistance face plate type of starter is shown in fig. 3, and requires a separate switch for control of the primary circuit. These are usually adaptable for motors up to 50 *h.p.* and when the full load current in the rotor circuit is less than 150 *amp.*

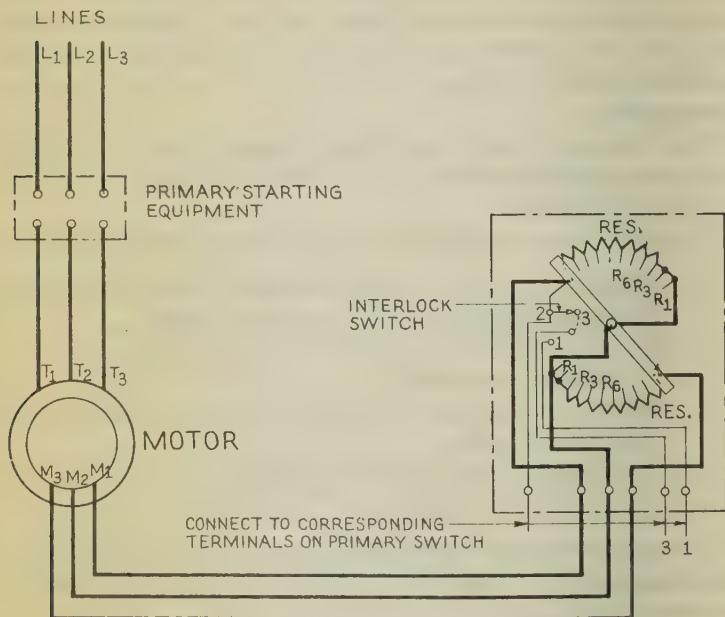


FIG. 3.—Connection diagram of wound rotor induction motor face plate starter.

As illustrated, the resistance is made up of three delta connected sections, but is connected in two phases only, the third being a fixed step. The starting lever is equipped with a spring similar to that used in direct current motor starters which

return it to the starting (all resistance) position when it is released. As an additional safety feature, the contact arm or lever cannot be left in the *full-in* position unless the primary (stator) contactor is closed nor can it be left in an intermediate position at any time.

Face Plate Starter and Speed Regulator.—A typical wiring diagram of a combined face plate starter and speed regulator for use in the rotor circuit of wound rotor induction motors, is shown in fig. 4. Starters of this type usually provide for a 50% speed reduction when the motor operates under full load at normal speed. They are usually built for motors in sizes up to 40 *h.p.* and for rotor currents up to 100 *amp.*

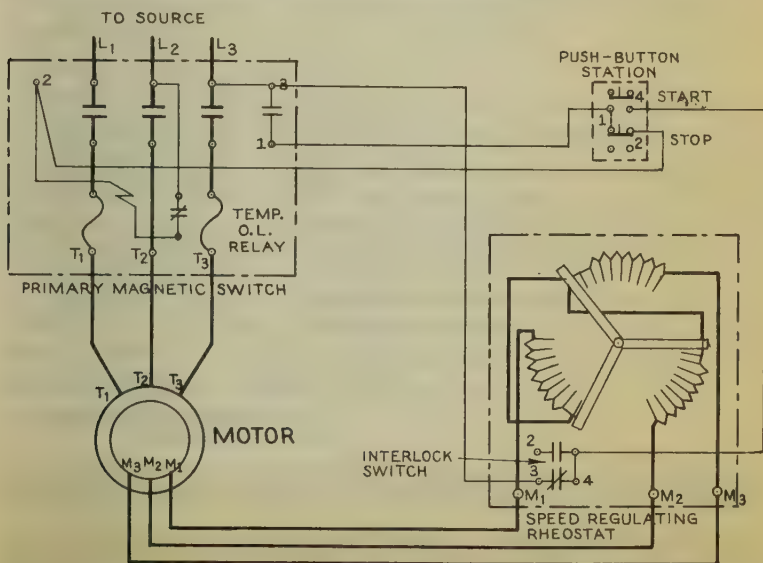


FIG. 4.—Wiring diagram of secondary speed regulating rheostat and primary magnetic switch for wound rotor induction motor.

Since the starter is not connected with the primary circuit of the motor, a magnetic switch, an oil circuit breaker, or similar device must be installed to control the primary circuit.

Multi-Switch Starters.—These are used in the secondary circuit of large wound rotor induction motors up to 2,000 *h.p.* with rotor currents up to 1,000 *amp.* A typical wiring diagram giving the circuit arrangement is shown in fig. 5.

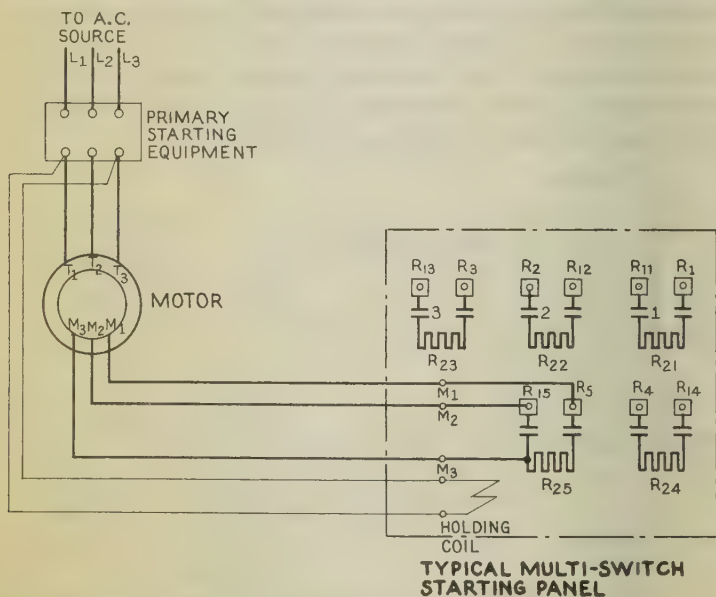


FIG. 5.—Wiring diagram showing connections of typical multi-switch starter for wound rotor induction motor.

The type of switch to be used in the primary (stator) circuit depends upon the voltage of the supply source. The resistor units in the secondary (rotor) circuit are balanced on all steps

of the controller. The contact levers are of the double pole type and are arranged in such a manner mechanically that they must be closed in a predetermined sequence, and only one at a time.

Since the switches are designed for hand-over-hand operation, a desirable time element is introduced which prevents too rapid acceleration of the motor. When the final switch has been closed, it is held in place by a magnetic coil, and because of the mechanical interlocking feature all other switches remain closed.

A failure of the motor supply source will cause the magnet coil to release the switches, returning the starter anew to the starting position with all the resistance in the secondary circuit. This type of starter is designed for starting duty only and is not suitable where speed regulation is required.

Drum Controllers.—These are employed very frequently for starting and speed control of wound rotor induction motors.

Because of their construction features they offer a compact, sturdy and dependable control means and also add to the safety of the operator. Drum controllers are built to handle both stator and rotor circuits, the cylinder mounting the contact segments being built in two insulated sections. They are also built to handle the rotor circuit only, in which case the stator circuit is being controlled by a circuit breaker or line starter. Other types are built for operation by means of an independent motor.

In addition to starting and regulating, speed regulating drum controllers are commonly used for speed reversing duty as well.

On small and medium size motors, face plate starters, such as described earlier in this chapter are commonly used, but with large motors drum controllers are generally preferred

because their contacts are heavier and better able to handle the heavy currents required.

Fig. 7 shows the connections of a typical drum controller for reversing and speed regulation duty used with a wound rotor motor.

The resistor material is mounted separately from the drum, and connections from the resistor are brought to the drum fingers.

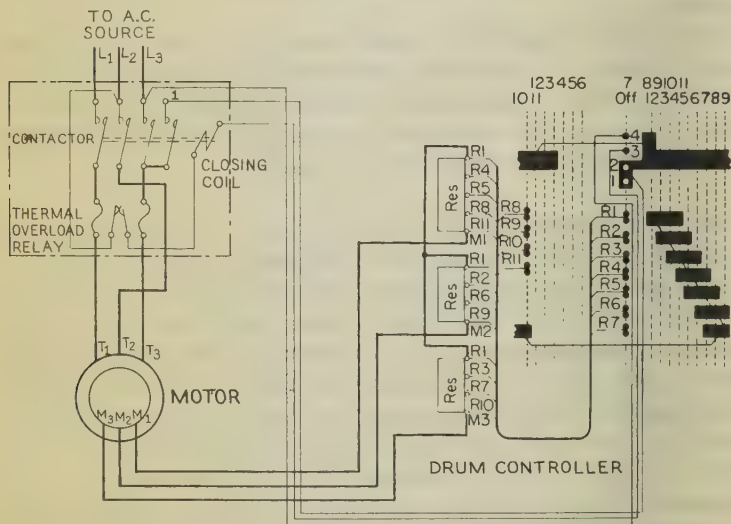


FIG. 6.—Wiring diagram of typical non-reversing drum controller for wound rotor induction motor with three-phase secondary.

The resistor connections, shown in fig. 7, are for starting the motor with one phase of its secondary open on the first point of the controller. When higher starting torque is desired, or when

connecting motor is rated above 80 *h.p.*, connect R_1 to R_{11} at the resistor and finger marked R_1 on controller to terminal R_3 on resistors. Resistor steps R_5 to R_6 , R_{15} to R_{16} and R_{25} to R_{26} are for resistance which remains permanently in the circuit. When these are not furnished, connect M_1 , M_2 and M_3 to R_5 and R_{15} and R_{25} as indicated by dotted lines.

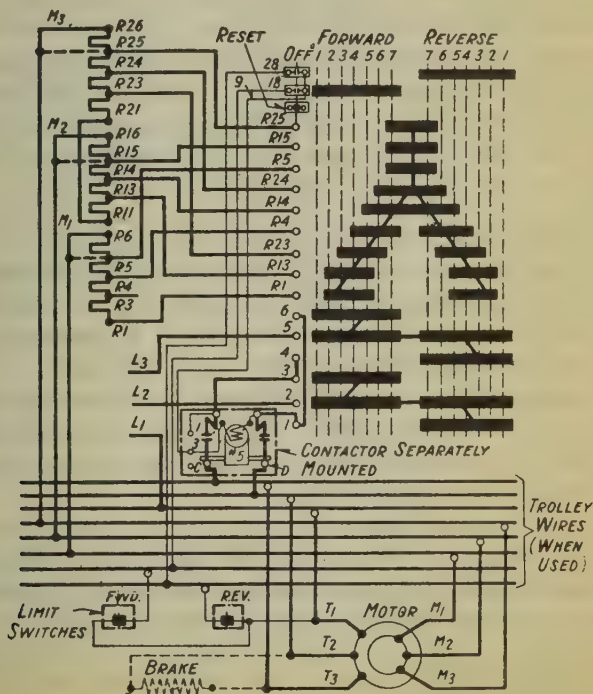


FIG. 7.—Wiring diagram for typical reversing and speed regulation drum controller as used with wound rotor induction motor.

Motor-Driven Drum Controllers.—These are used in certain drives requiring close automatic speed regulation such as in large air conditioning plants, blowers, stokers, etc.

In construction these controllers differ from those previously described in that cam operated switches are used in place of the segments and fingers.

These drums are built with either 13 or 20 balance speed-regulating points, and the cam switch construction saves space when so many balanced points are needed. Each switch carries two contacts, both of which are connected to the middle leg of the resistor. They make contact simultaneously with stationary contacts, one connected to each of the outside legs of the resistor. In this way the closing of any cam-operated switch short-circuits the resistor at that point.

The drum is driven by a small motor connected to the drum shaft through suitable gearing. The pilot motor is energized by some automatic device such as a thermostat or a regulator.

A typical motor-driven drum may have 20 balanced speed points and be rated at 600 amperes and 1,000 volts. It may have a positioning device which insures that the pilot motor stops only at positions in which the switches are fully closed. It may also have self-contained limit switches to stop the motor at each end of the drum travel.

Magnetic Starters.—When used for starting and control of wound rotor motors, magnetic starters are built in three different forms depending upon the duty of the motor as:

1. Plain starting.
2. Speed regulating.
3. Speed setting.

Magnetic starters consist of a magnetic contactor for connecting the stator circuit to the line and one or more accelerating contactors to commute the resistance in the rotor circuit.

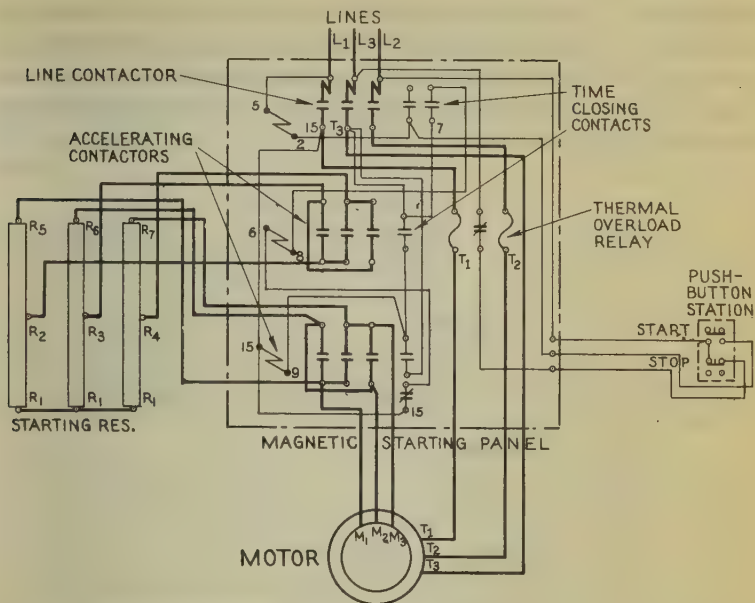


FIG. 8.—Wiring diagram illustrating connection of magnetic contactor panel for wound rotor induction motor. (Non-reversing duty.)

The number of secondary accelerating contactors varies with the rating, a sufficient number being employed to assure smooth acceleration and to keep the inrush current within practical limits. The operation of the accelerating contactors is controlled by a timing device which provides definite time acceleration. For high tension service, the primary contactor is usually of the oil immersed type.

Magnetic starting speed regulators are very similar to the magnetic starters except that the secondary circuit is controlled by a series of magnetic contactors which are operated from a dial switch in the control station or by a face plate type rheostat mounted in the controller itself. Where the magnetic contactor construction is used, they also act as accelerating contactors on starting. If a rheostat is used the motor is accelerated up to the speed for which the rheostat is set, by means of accelerating contactors on the panel.

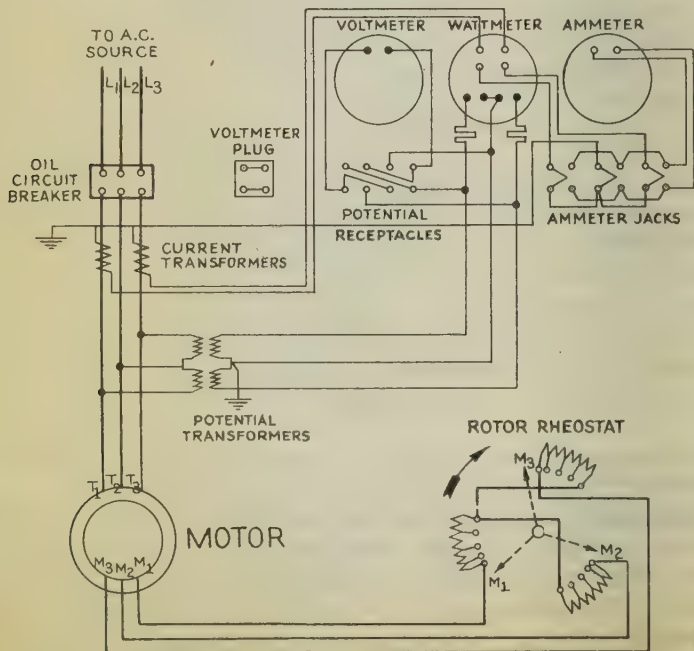


FIG. 9.—Wiring diagram showing connection of manually operated wound rotor induction motor and associated meters.

Resistors.—All standard wound rotor phase circuits, whether for two- or three-phase circuits, have their secondaries wound for three-phase. The resistors for each phase, used with these motors, are identical with the exception of the terminal marking.

The resistor for the first phase has its terminals marked consecutively R_1, R_2, R_3 , etc. The second phase R_{11}, R_{12}, R_{13} , etc., the third phase R_{21}, R_{22}, R_{23} , etc. The actual resistor will consist of 1, 2, 3 or multiples of these frames of tubes or grids.

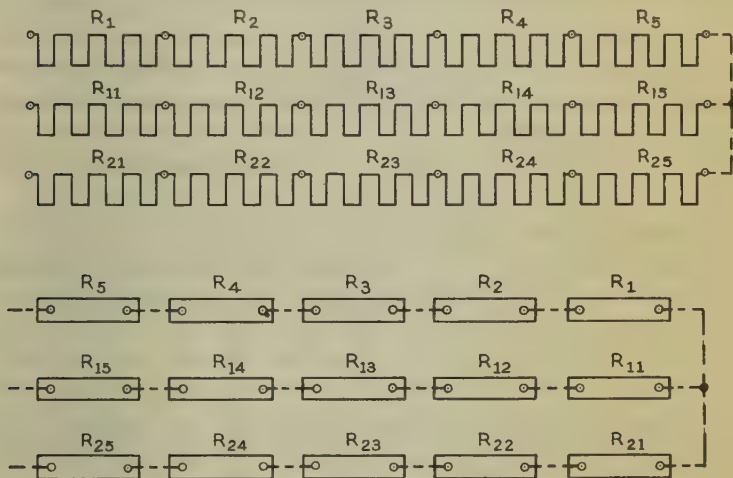


FIG. 10.—Typical representation of secondary resistor units and their connections.

Secondary resistors for wound rotor induction motors are as a rule designed for star connection. Resistors for most manual controllers may be connected with all three secondary phases closed or with one secondary phase open on the first point of the controller.

Resistors for magnetic controllers are connected with all three phases closed in the secondary on the first point.

The torque obtained with a resistor of a given class number varies with the connection used on the first point of the controller.

The NEMA resistor classification for wound rotor induction motors are given in table 1. For example, Class 114 is for starting duty only and on basis that motor should be started and brought up to speed in approximately five seconds with a minimum of 75 seconds between successive starts.

TABLE 1

NEMA CLASSIFICATION

Per Cent Full Load Current on First Point	STARTING TORQUE % OF FULL LOAD					RESISTOR CLASS NUMBER						
	Series Motors	Compound Motors	Shunt Motors	Wound Rotor Induction Motors		5 Sec. on Out of 80 Sec.	10 Sec. on Out of 80 Sec.	15 Sec. on Out of 90 Sec.	15 Sec. on Out of 60 Sec.	15 Sec. on Out of 45 Sec.	15 Sec. on Out of 30 Sec.	Cont.
				1 Ph. Stg.	3 Ph. Stg.							
25	8	12	25	15	25	111	131	141	151	161	171	91
30	30	40	50	30	50	112	132	142	152	162	172	92
70	50	60	70	40	70	113	133	143	153	163	173	93
100	100	100	100	55	100	114	134	144	154	164	174	94
150	170	160	150	85	150	115	135	145	155	165	175	95
200	250	230	200		200	116	136	146	156	166	176	96

The capacity of resistors depends largely upon the ventilating space. As a rule the resistor frames should never be stacked more than four in height, and when space is available, each frame should be separated from the next by approximately the width of the end frame. Frames may be mounted on the floor, platform or on the wall, but in such a way so as to obtain free ventilation.

In this connection it may also be pointed out the necessity for close periodic inspection of resistors and associated connections. This inspection should include the tightening of loose lock nuts, connections, etc. The collection of dirt and dust should be blown out from between the resistor units.

Application of Wound Rotor Motors

General.—Wound-rotor motors have the ability to start extremely heavy loads, hence they are suitable for (1) driving various types of machinery which require development of considerable starting torque to overcome friction; (2) accelerating extremely heavy loads which have flywheel effect or inertia, and (3) overcoming back-pressures set up by fluids and gases in the case of reciprocating pumps and compressors.

Double squirrel-cage motors are also applicable on many of the heavier machines involving the problems mentioned above. However, if a considerable length of time be required to accelerate the load to full speed, double squirrel cage rotors may burn out before full speed is attained, and for that reason wound-rotor motors should be used instead. Where high starting torque alone is involved, double squirrel-cage motors will qualify, but the fact that all the heat developed in the secondary circuit is confined to the rotor prevents their use if the starting period be too long. Frequent starting has the same effect of overheating double squirrel-cage motors, for which reason wound-rotor motors should be used on machinery started frequently.

Operating Speed Variation.—Variations in operating speed are essential on many applications. It is often desirable to vary the operating speed of conveyors, compressors, pul-

verizers, stokers and the like in order to meet varying production requirements. Wound-rotor motors, because of their adjustable varying speeds, are ideally suited for such applications. However, if the torque required does not remain constant, the speed of the wound-rotor motor will vary over wide limits, a characteristic constituting one of the serious objections to the use of wound-rotor motors for obtaining reduced speeds. Another factor which must be taken into consideration when selecting wound-rotor motors for reduced speed operations, is that of lowered motor efficiency.

It is suitable where the speed range required is small; where the speeds desired do not coincide with a synchronous speed of the line frequency; or where the speed must be gradually or frequently changed from one value to another.

The wound-rotor motor also gives high starting torque with a low current demand from the line, but it is not efficient when used a large proportion of the time at reduced speed, since power corresponding to the percent drop in speed is consumed in the external resistance without doing any special work.

The wound-rotor motor can operate at any speed from its maximum full-load speed down to almost standstill. Speed reduction below one-half is not recommended, however, both on account of the poor speed regulation (the no-load speed is always synchronous speed) and on account of the increased heating of the motor due to the decreased ventilation.

When wound-rotor motors are used for cranes, hoists and elevators, machinery operated intermittently and not over long periods, poor speed regulation and loss in efficiency are of little consequence. However, if lowered speed is required over longer periods, poor speed regulation and loss in efficiency may become prohibitive.

Smooth Starting.—By the use of external resistors in the slip ring rotor windings, a wide variation in rotor resistance can be obtained with a resultant variation in acceleration characteristics. Thus a heavy load can be started as slowly as desired, without a jerk, and can be accelerated smoothly and uniformly to full speed. It is merely a matter of supplying the necessary auxiliary control equipment to insert sufficiently high resistance at start, and to gradually reduce this resistance as the motor picks up speed.

Low Starting Current.—Many power companies have established limitations on the amount of current motors may draw at starting. The purpose is to reduce voltage fluctuations and prevent flickering of lights. Because of such limitations, the question of starting current is often the deciding factor in the choice of wound-rotor motors instead of squirrel cage motors.

Wound-rotor motors with proper starting equipment develop a starting torque equal to 150% of full load torque with a starting current of approximately 150% of full load current, which compares very favorably with squirrel-cage motors, one type of which requires a starting current of as much as 600% of full load current to develop the same starting torque of 150%.

Fynn-Weichsel Motors.—The power factor of an induction motor depends upon a number of factors such as speed, rating and design characteristics, and is always less than unity. Also the power factor varies with the load on the motor. These reasons have led power companies (who must supply the additional capacity to take care of this additional magnetizing current) and motor users who must pay for this additional current and capacity, to search for a motor that would (a) satisfactorily solve the power factor problem; (b) operate at syn-

chronous speeds; (c) be easy to start, and (d) have high starting torque and a high pull-in torque.

These demands have led to the introduction of a motor known as the *Fynn-Weichsel* motor. This motor may be classified as a slip ring induction synchronous motor; that is, it starts as a slip ring induction motor and after attaining synchronous speed, it becomes a self-excited synchronous motor.

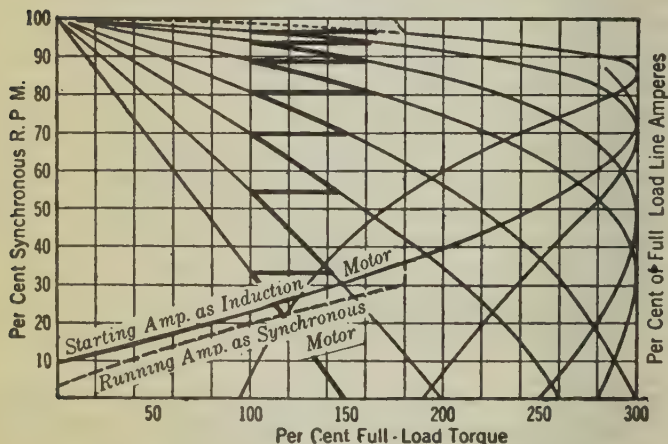


FIG. 11.—Starting characteristics of Fynn-Weichsel motors are identical with those of wound rotor induction motors, with this difference, however, that the usual wound rotor motor has a running speed with full load of approximately 95% of the synchronous speed while the Fynn-Weichsel motor operates at synchronous speed. The motor continues to increase in speed, without change in operating connections, until synchronism is reached. The starting torque up to the point of pull-in is the same as that of a well-designed wound rotor motor. During the interval of change from induction to synchronous operation, the torque is in excess of full-load torque.

The rotor is provided with slip rings and also with a small commutator. It has two windings, one in the bottom of the slots, connected to the commutator, and the other in the top of the slots connected to the slip rings.

The stator similarly has two windings arranged 90 electrical degrees apart, one being short circuited when running and the other connected to brushes riding on the commutator.

In starting, line voltage is applied to the motor through the slip rings, and resistance is introduced in both of the stator windings during the starting period.

The starting characteristics shown in fig. 11 are identical with those of an induction motor, with the difference, however, that the usual slip ring motor has a running speed at full load of approximately 95% of synchronous, while the Fynn-Weichsel motor operates at synchronous speed.

After the motor attains synchronous speed, it becomes a self-excited synchronous motor. It is claimed that as a synchronous motor it will carry 150% or more load without falling out of step. Above synchronous load, the motor will operate as an induction motor and continue to do so to the "breakdown point" which is usually about 250% of the full load torque.

It is further claimed that for each horse power of medium and high speed *Fynn-Weichsel* motors installed, its leading magnetizing amperes counteract the lagging magnetizing amperes of induction motors of the same horse power and speed giving substantially unity power factor of the combined load of the two types of motors. It accomplishes this correction irrespective of the load on the two types of motors.

However, if the lagging magnetizing amperes of slow speed induction motors are to be counter balanced by the leading magnetizing amperes furnished by *Fynn-Weichsel* motors of

corresponding speed, a greater proportion of *Fynn-Weichsel* capacity will be required to obtain unity power factor due to the large magnetizing current required by slow speed induction motors.

Although it is generally more economical to employ over-excited synchronous motors for power factor correction, especially on large systems, each motor should be judged on its own merits and should be chosen only after competent engineers and manufacturers have been consulted as to its adaptability for its particular duty.

In addition to employment for power factor correction, this type of motor is also used to drive air and refrigeration compressors also in rolling mills and generally for loads with a heavy fly-wheel effect of inertia.

The *Fynn-Weichsel* motor is manufactured by the *Wagner Electric Corporation, St. Louis, Mo.*, in sizes up to 200 h.p. and for voltages up to 550 volts.

CHAPTER 11

Fractional Horsepower Motors

By definition, a fractional horsepower motor *is a motor built on a frame smaller than that having a continuous rating of one horsepower, open type, at 1,700-1,750 revolutions per minute.*

It should be noted, however, that this does not indicate that the horsepower is *less than one*, because a 1-h.p. 3,450 r.p.m. 60 cycle motor is a *fractional* rating, while a $\frac{3}{4}$ h.p. 1,140 r.p.m., for example, is an *integral* rating.

Single-Phase Motor Classification.—Single-phase motors may be divided into several classes, depending upon construction and method of starting, as:

1. Split-phase.
2. Capacitor start.
3. Capacitor.
4. Repulsion.
5. Shaded pole.
6. Universal, etc.

The Split-Phase Induction Motor.—This motor is one of the most popular of the fractional horsepower types. Fig. 1 shows an arrangement of the windings. The motor consists essentially of a squirrel cage rotor, and has two stator windings, a

main winding and a starting winding. The main winding is connected across the supply lines in the usual manner, and has a low resistance and a high inductance. The starting or auxiliary winding which is physically displaced in the stator from the main winding, has a high resistance and a low inductance.* This physical displacement, in addition to the electrical phase displacement produced by the relative electrical resistance values in the two windings, produce a weak rotating field which is sufficient to provide a low starting torque.

After the motor has accelerated to 75 or 80% of its synchronous speed, a starting switch (usually centrifugally operated) opens its contacts to disconnect the starting winding.

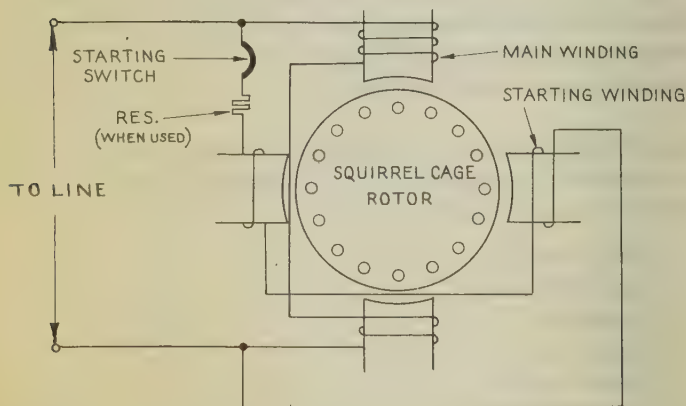


FIG. 1.—Schematic diagram illustrating circuit arrangement of a split phase induction motor.

*NOTE.—Unless otherwise specified, however, the auxiliary circuit is assumed to be opened when the motor has attained a predetermined speed. The term split phase motor, used without qualification, describes a motor to be used without impedance, other than offered by the motor windings themselves, other types being separately defined.

The function of the starting switch is to prevent the motor from drawing excessive currents from the line and also to protect the starting winding from damage due to heating. The motor may be started in either direction by reversing either the main or auxiliary winding.

The characteristics of a resistance type split-phase motor is shown in fig. 2. The split phase motor is most commonly used in sizes ranging from $1/30$ to $1/2$ h.p. for applications such as fans, business machines, automatic musical instruments, buffing machines, grinders and numerous other applications.

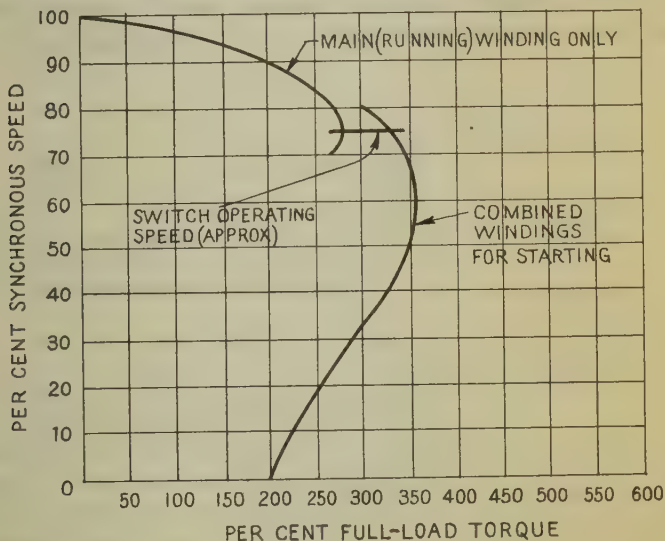


FIG. 2.—Typical speed torque characteristics of a split-phase induction motor.

The Resistance-Start Motor.—This is a form of split phase motor having a resistance connected in series with the auxiliary winding. As in the split phase motor, the auxiliary circuit is opened when the motor has attained a predetermined speed.

The Reactor-Start Motor.—This is a form of split-phase motor designed for starting with a reactor in series with the main winding. The reactor is short circuited or otherwise made ineffective and the auxiliary circuit is opened when the motor has attained a predetermined speed. A circuit arrangement of the motor is shown in fig. 3. The function of the reactor is to reduce the starting current and to increase the angle of lag of the main winding current behind the voltage. This motor will develop approximately the same torque as the split-phase motors discussed previously.

The centrifugally operated starting switch must be of the single-pole double-throw type for proper functioning.

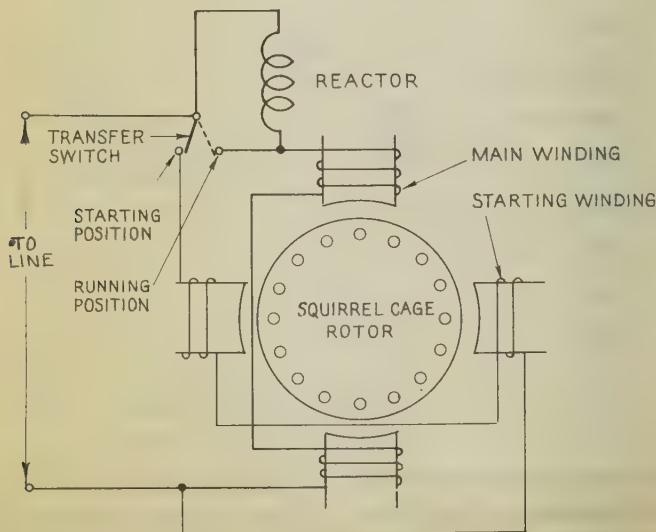


FIG. 3.—Circuit arrangement of a reactor-start motor.

The Capacitor-Start Motor.—This is another form of split-phase motor having a capacitor or condenser connected in series with the auxiliary winding. The auxiliary circuit is opened when the motor has attained a predetermined speed. The circuit, fig. 4, shows the winding arrangement.

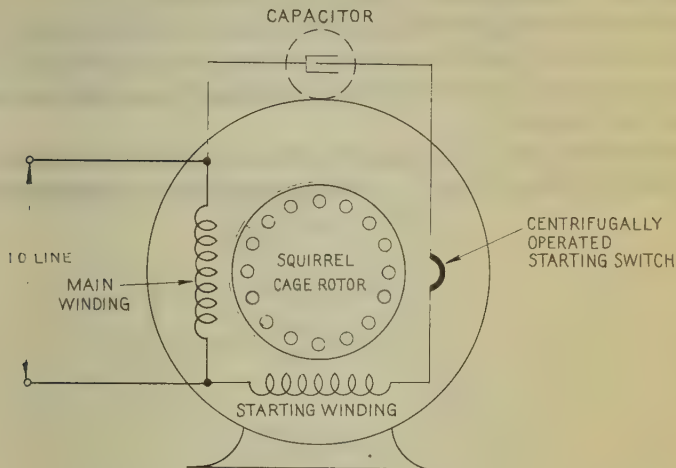


FIG. 4.—Circuit arrangement of a capacitor-start motor.

The rotor is of the squirrel cage type as in other split-phase motors. The main winding is connected directly across the line, while the auxiliary or starting winding is connected through a capacitor which may be connected into the circuit through a transformer with suitably designed windings and capacitor; the two windings will be approximately 90° apart electrically.

This type has certain advantages over the previously described types in that it has a considerably higher starting torque accompanied by a high power factor.

The Capacitor Motor.—This form of single-phase induction motor has the main winding connected directly to the power supply and the auxiliary winding connected in series with a capacitor. The capacitor and auxiliary winding remains in the circuit while the motor is in operation. There are several types of capacitor motors differing from one another, mainly in the number and arrangement of capacitors employed.

The running characteristics of this type of motor are extremely favorable and the torque is fixed by the amount of additional capacitance added to the auxiliary winding during the starting period.

The simplest type mechanically is the *low* torque, permanent-split capacitor-motor, fig. 5. Here a capacitor is permanently

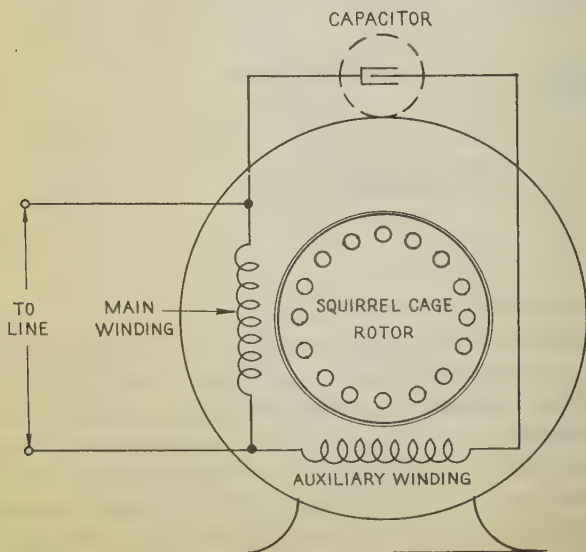


FIG. 5.—Circuit arrangement of a permanent capacitor split-phase motor.

connected in series with the auxiliary winding. This type of motor can be arranged for adjustable-varying speed by the use of a tapped winding or autotransformer regulator.

High torque motors are usually provided with one running and one starting capacitor connected in parallel as shown in fig. 6, or by means of an autotransformer connected to increase the voltage of the capacitor during the starting period, as indicated in fig. 7.

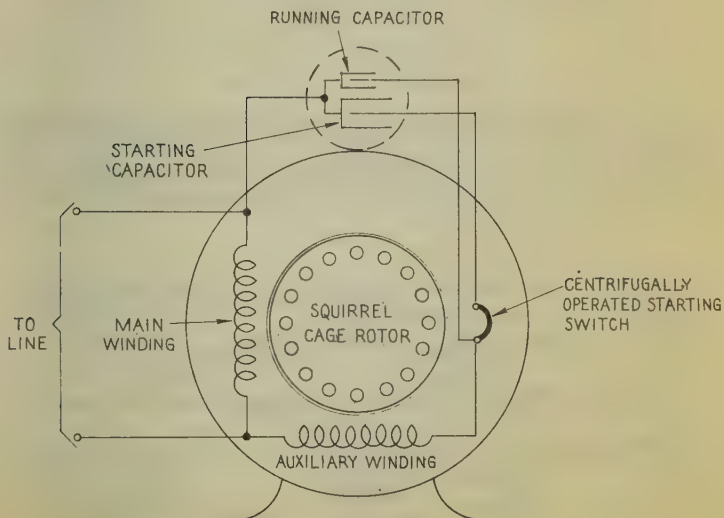


FIG. 6.—Circuit arrangement in a high torque type capacitor motor.

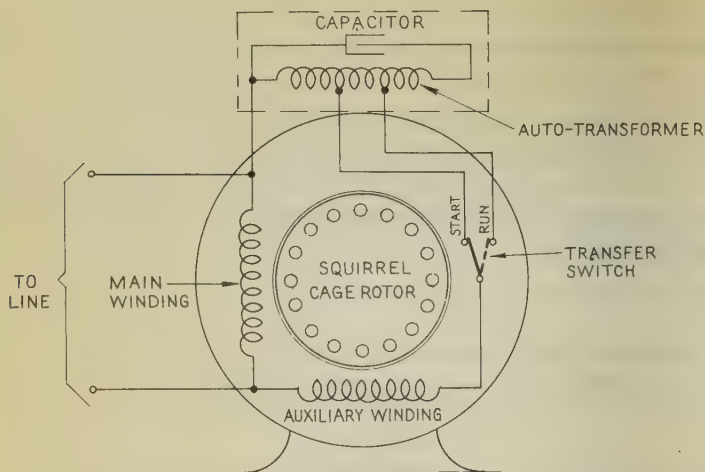


FIG. 7.—Circuit arrangement in a high torque type capacitor motor using auto-transformer. In a circuit arrangement of this type, a single pole, double throw transfer switch connects the capacitor in such a way as to provide a voltage of approximately 700 volts at starting. After the motor has reached a predetermined speed, the transfer switch operates and connects the capacitor to a permanent running voltage which is approximately 300 volts.

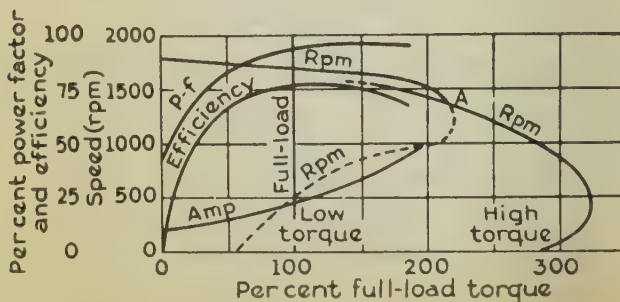


FIG. 8.—Typical operating characteristics of high and low torque type capacitor motors.

The Repulsion Motor.—This is a single-phase motor which has a stator winding arranged for connection to the source of power and a rotor winding connected to a commutator. Brushes on the commutator are short-circuited and are so placed that the magnetic axis of the rotor winding is inclined to the magnetic axis of the stator winding. This type of motor has a varying speed characteristic.

Principally it has a stator like that of a single-phase motor, but has a rotor like the armature of a direct current motor, with the opposite brushes on the armature short-circuited, that is, connected together by a connector with a negligible resistance.

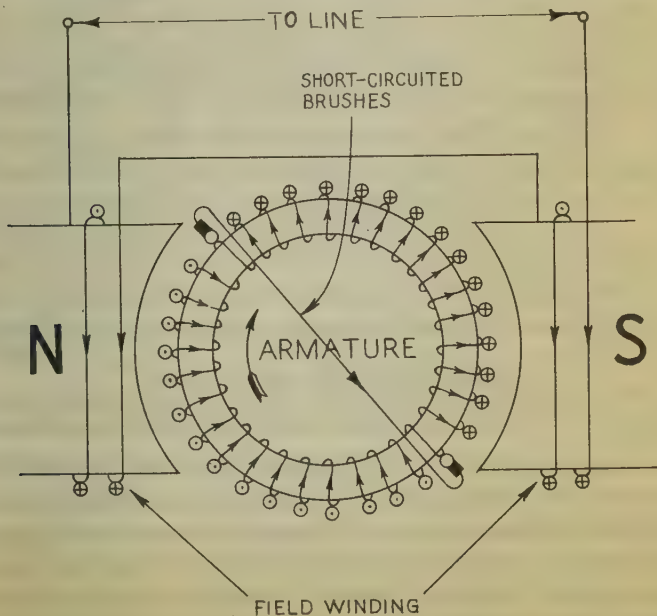


FIG. 9.—Circuit arrangement of a simple series repulsion motor.

The brushes are placed so that a line connecting them makes a small angle with the neutral axis of the magnetic field of the stator. The stator induces a current in the armature which produces an armature field with poles in the neighborhood of the brushes. These have the same polarity as the adjacent field poles and are repelled by them so that this repulsion causes the armature to revolve. From this action the motor derives its name.

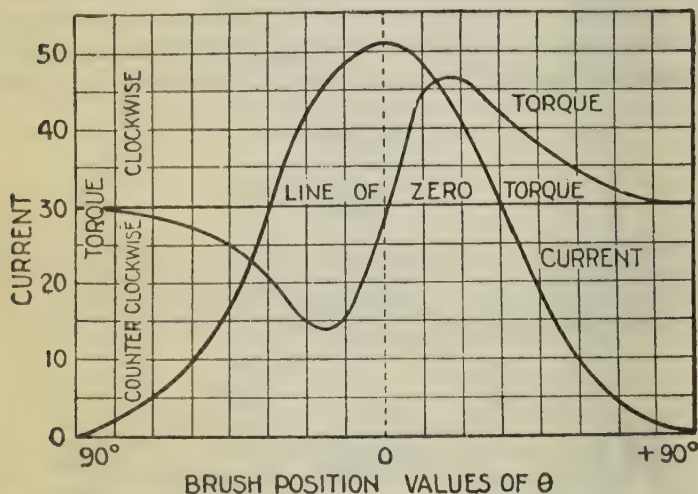


FIG. 10.—Curves for repulsion motor showing the effect on current and torque due to shifting of the brushes. Note that the current and torque vary greatly with the position of the brushes.

A repulsion motor of this original type has characteristics similar to the series motor. It has a high starting torque and moderate starting current. It has low power factor except at high speeds. For this reason it is often modified into the "compensated repulsion motor," which has another set of brushes placed midway between the short-circuited set and this added set is connected in series with the stator winding.

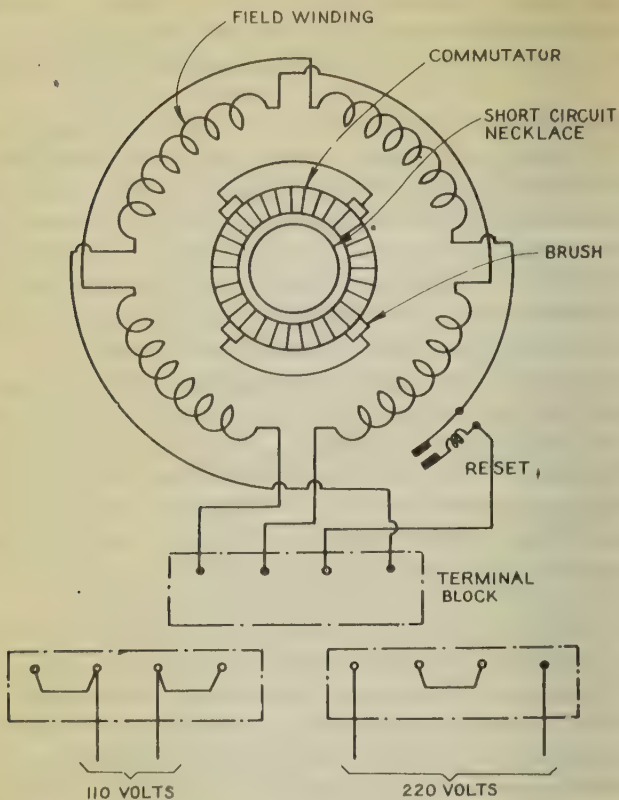
Compensated Repulsion Motor.—This is simply a repulsion motor with an added winding to improve the power factor. It may be designed with constant or varying speed characteristics.

Repulsion-Start Induction Motor.—This type of single-phase motor is widely used in sizes up to about five horsepower. A repulsion start induction motor is a single-phase motor having the same windings as a repulsion motor, but at a predetermined speed the rotor winding is short circuited or otherwise connected to give the equivalent of a squirrel cage winding. This type of motor starts as a repulsion motor but operates as an induction motor with constant speed characteristics.

The repulsion start induction motor has a single-phase distributed field winding with the axis of the brushes displaced from the axis of the field winding. The armature has an insulated winding. The current induced in the armature or rotor is carried by the brushes and commutator resulting in high starting torque. When nearly synchronous speed is attained the commutator is short circuited so that the armature is then similar in its functions to a squirrel cage armature.

The photographs, fig. 12 and 13, show the working principles of the mechanism for simultaneously lifting the brushes and short circuiting the commutator to change the operation from *repulsion* to *induction*. The object of lifting the brushes is to eliminate wear of the commutator during the running periods as it makes no difference electrically whether the brushes be in contact or not after the motor comes up to speed.

This motor has gone through many stages of improvement since its first appearance on the market, although its general principle has remained the same. The general reliability of this type of motor is largely governed by the reliability of the short circuiting mechanism. For this reason, it has been the



NOTE: TOP TERMINAL SHOWS CONNECTION TO MOTOR WINDINGS ONLY. FOR PROPER CONNECTION TO A.C. CIRCUIT CHECK VOLTAGE SOURCE AND CONNECT AS INDICATED ON LOWER TERMINALS.

FIG. 11.—Typical coil relationship in single-phase repulsion-start induction motor.

constant aim of engineers to improve on the principle and construction of the short circuiting switch. Centrifugal force, as a means to accomplish the best results, was early resorted to and still remains the most practical method, because the weight being once determined, will always throw out and short circuit the commutator at the same speed.

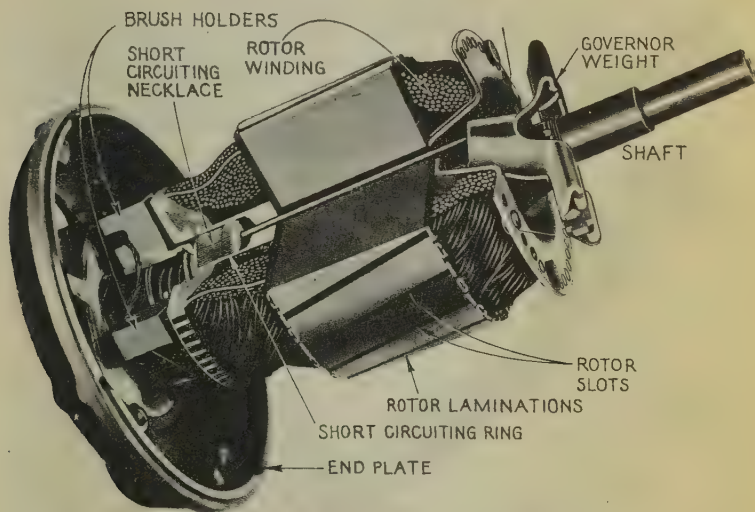


FIG. 12.—Shows position of short-circuiting necklace and brush mechanism while motor is starting.

Since the motor starts on the repulsion principle, it has the same starting characteristics as the repulsion motor described previously, namely, high starting torque and low starting current.

As the motor speeds up the torque falls off rapidly. At some point on the speed torque curve after the repulsion curve has crossed the induction motor curve, usually at about 80% of

synchronism, the commutator is automatically short circuited, producing the effect of a cage winding in the armature, and the motor comes up to speed as an induction motor.

After the commutator has been short circuited, the brushes do not carry current and, therefore, may be lifted from the commutator, but lifting the brushes is not necessary.

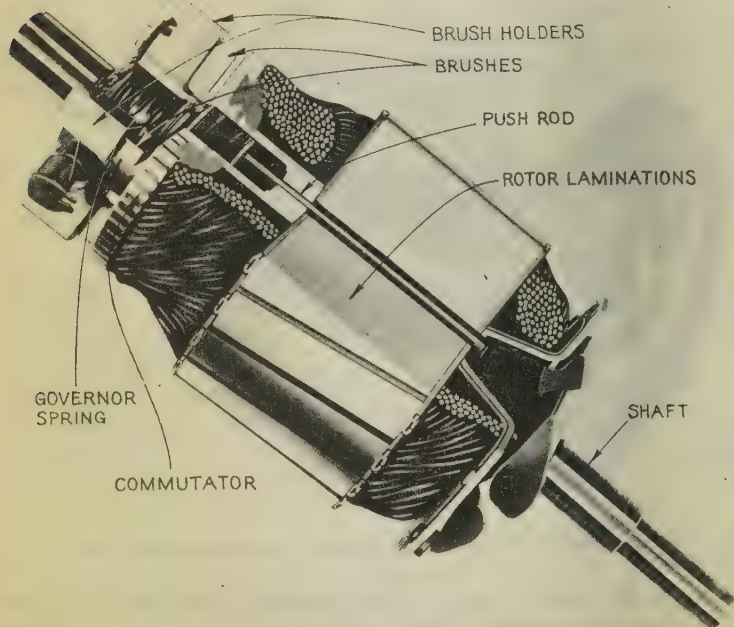
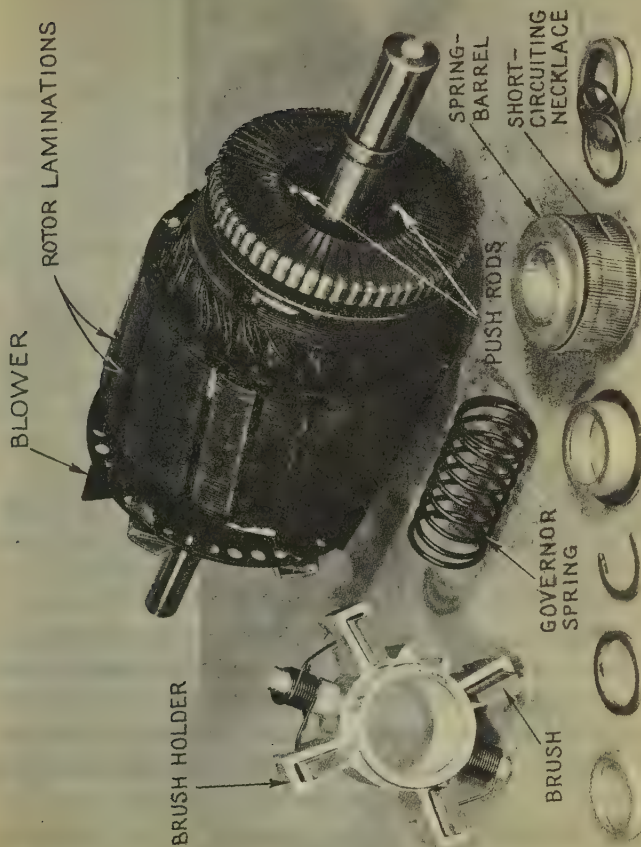


FIG. 13.—Shows position of short-circuiting necklace and brush mechanism after governor weights have operated.

The curve in fig. 18 shows the speed torque characteristics of a typical repulsion-start induction motor. The short circuiting mechanism operates at point A. At this point the induction



FIGS. 14 TO 17.—Dismantled rotor showing items making up short-circuiting and brush-lifting mechanism. Governor-weights (not shown) are at opposite end of rotor.

motor torque is greater than the repulsion motor torque, which means that if the repulsion winding has sufficient torque to bring the load up to this speed, there will be sufficient torque as an induction motor to bring the load up to full speed.

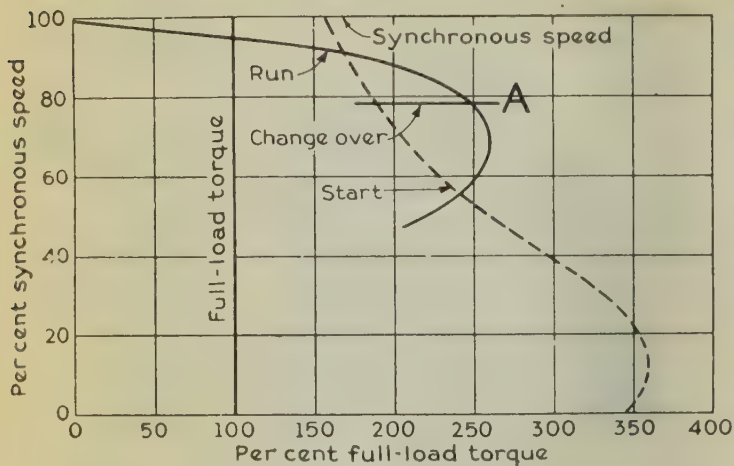


FIG. 18.—Speed-torque characteristics of a typical repulsion-start induction motor.

The higher the speed at which the short circuiting mechanism operates, the lower will be the induction motor current at that point and consequently the less disturbance to the line. After the commutator has been short circuited, the motor has the same characteristics as the single phase induction motor previously described.

If the short circuiting mechanism operates before the repulsion curve crosses the induction motor curve, and the torque of the induction motor be less than that required to accelerate the load, the motor may slow down until the short circuit is re-

moved from the commutator, in which case the motor will again operate repulsion. The armature will then speed up until the commutator is again short circuited after which the armature will slow down until it again becomes repulsion. This cycle will be repeated over and over again until some change takes place.

The efficiency and maximum running torque of the repulsion start induction motor are usually less than those of a cage wound induction motor of comparative size. In other words, the repulsion start induction motor must be larger than cage wound motor of the same rating to give the same performance.

Repulsion Induction Motors.—This is another form of repulsion motor which has a squirrel cage winding in the rotor in addition to the repulsion motor winding. A motor of this type may have either a constant speed or varying speed characteristics.

Specifically this motor is a combination of the repulsion and induction types and operates on the combined principle of repulsion and induction. It is sometimes termed a *squirrel cage repulsion motor*. In this motor the desirable starting characteristics of the repulsion motor and the constant speed characteristics of the induction motor is obtained. It is of course impossible to combine the two types of motor and obtain only the desirable characteristics of each.

The field has the same type of windings as used in the repulsion start induction motor. The armature has two separate and independent windings. They are:

1. Squirrel cage winding, and
2. Commutated winding.

Both of these armature windings function during the entire

period of operation of the motor. There are no automatic devices such as the starting switch of the split phase motor, or the short circuiting device of the repulsion start induction motor.

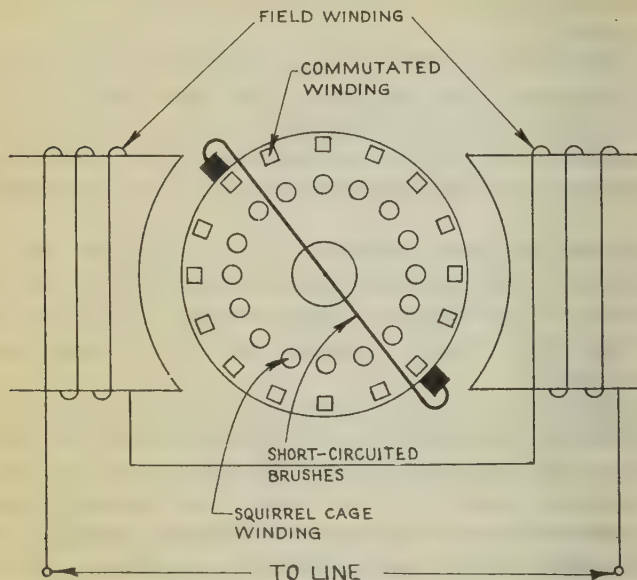


FIG. 19.—Illustrating circuit arrangement of a repulsion induction motor.

The cage winding is located in slots below those which contain the commutated winding. The slots which contain the two windings may or may not be connected by a narrow slot. Usually there are the same number of slots in the two windings. It is not, however, absolutely essential that they be the same.

Due to its construction, the squirrel cage winding has inherently a high inductance. Its reactance with the armature at rest is, therefore, high.

The commutated winding has a low reactance and the current will flow mainly in this winding. The ideal condition at starting would be for all of the flux to pass beneath the commutated winding and none of it to pass beneath the cage winding. If this condition could be obtained, this motor would have the same starting characteristics as the repulsion start induction motor.

At full load speed, which is slightly below synchronism, the reactance of the cage winding is low, and most of the mutual flux passes beneath the cage winding.

Both windings produce torque and the output of the motor is the combined output of the cage winding and the commutated winding.

The commutation of the motor is good at all speeds. The no-load speed is above synchronism and is limited by the combined effect of the field winding on the commutated winding and the cage winding and the action of the two armature windings on each other. At synchronous speed, a squirrel cage motor has no torque. At synchronous speed, and for a short distance above synchronous speed, the torque of a repulsion induction motor is greater than that of the commutated winding alone, which shows that due to the interaction between the two armature windings, the squirrel cage supplies torque instead of acting as a brake.

At full load speed, and up to about the maximum running torque point, the torque of this motor is greater than the sum of the torques of the cage winding and the commutated winding. The inherent locked torque curve of a repulsion induction motor is similar to that of the repulsion motor shown in fig. 20. At soft neutral, the primary winding carries the squirrel cage current in addition to the exciting current of the motor. Since the starting current of the repulsion induction motor is low, it

may be operated from lighting circuits when driving frequently starting devices.

The repulsion induction motor is especially suitable for such applications as household refrigerators, water systems, garage air pumps, gasoline pumps, compressors and similar applications.

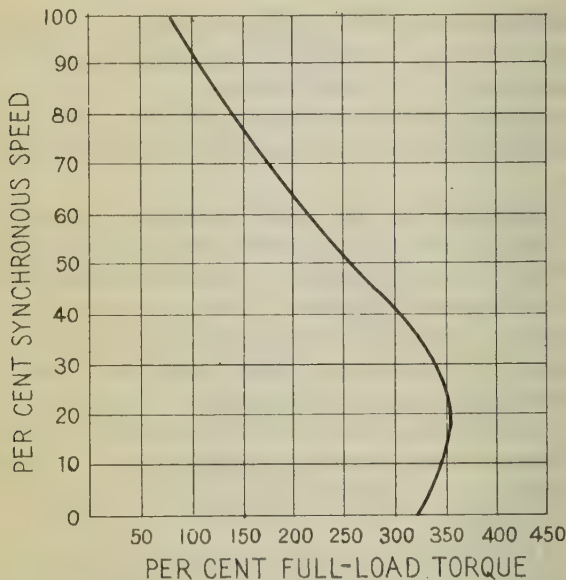


FIG. 20.—Speed-torque characteristics of a typical repulsion induction motor.

The Shaded Pole Motor.—This is a single phase induction motor equipped with an auxiliary winding displaced in magnetic positive form, and connected in parallel with, the main winding.

These are manufactured in fractional horsepower sizes, and have found employment in a variety of household appliances such as fans, blowers, hair driers and other applications requiring a low starting torque. It is operated only on alternating current, usually nonreversible, is low in cost and extremely rugged and reliable.

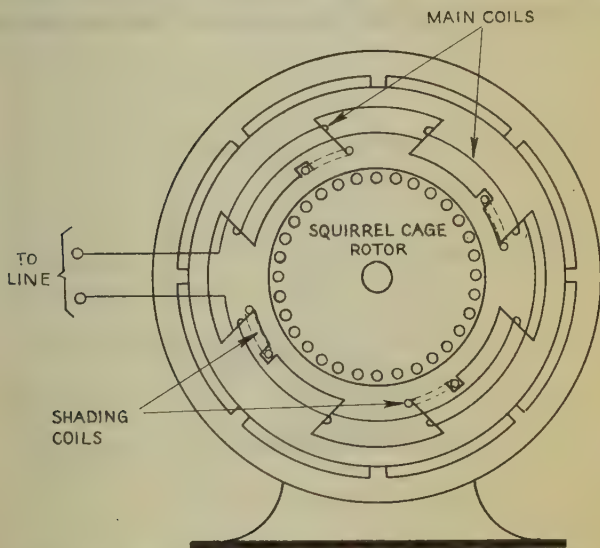


FIG. 21.—Single-phase fan motor with *shading coils* for starting. In addition to the main field coils, one tip of each pole piece is surrounded by a short circuited coil of wire or frame of copper, as indicated in the figure. This coil, or copper frame, is called a shading coil, and it causes a phase difference between the pulsating flux that emanates from the main portion of each polar projection and the pulsating flux which emanates from the pole tip, thus introducing an approach to two-phase action on the armature.

Although there are a number of different construction methods employed, principally the motor operates as follows:

The shading coil (from which the motor has derived its name) consists of low resistance copper links embedded in one side of each stator pole, and are used to provide the necessary starting torque. When the current increases in the main coils a current is induced in the shading coils, that opposes the magnetic field building up in the part of the pole pieces they surround. This produces the condition shown in fig. 22, where the flux is crowded away from the portion surrounded by the shading coil.

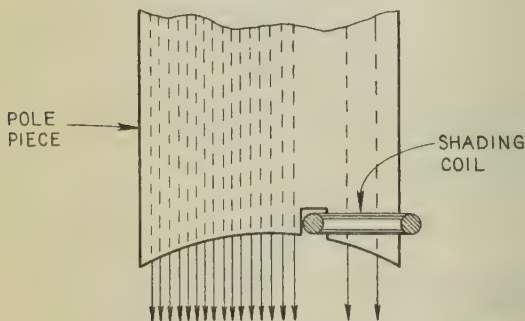


FIG. 22.—Diagram showing action of shading coil in alternating current motor. The extremities of these pole pieces are divided into two branches, in one of which a copper ring called a *shading coil* is placed as shown, while the other is left *unshaded*. The action of the shading coil is as follows: Consider the field poles to be energized by single phase current and assume the current to be flowing in a direction to make a north pole at the top. Assume the poles to be just at the point of forming. Lines of force will tend to pass through the shading coil and the remainder of the pole. Any change of lines within the shading coil generates a voltage, which causes to flow through the coil a current of a value depending on the voltage, and always in a direction to oppose the change of lines. The field flux is, therefore, partly shifted to the free portion of the pole, while the accumulation of lines through the shading coil is retarded.

When the main coil current decreases, that in the shading coils also decreases until the pole pieces are uniformly magnetized. As the main coil current and the pole piece magnetic flux continue to decrease, current in the shading coils reverses and tends to maintain the flux in part of the pole pieces.

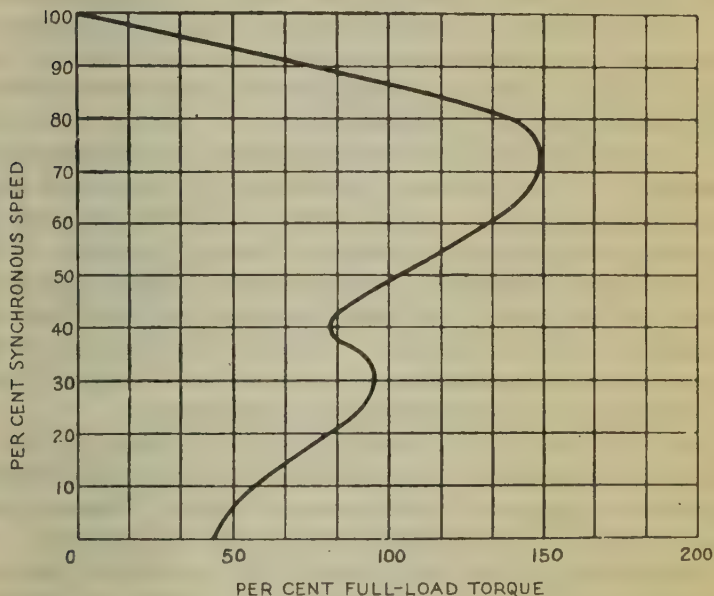


FIG. 23.—Speed torque characteristics of a typical shaded pole motor.

When the main coil current drops to zero, current still flows in the shading coils to give the magnetic effect which causes the coils to produce a rotating or magnetic field which makes the motor self-starting.

The Universal Motor.—A universal motor is a series-wound or compensated series-wound motor which may be operated either on *direct current* or on single-phase *alternating current* at approximately the same speed and output. These conditions must be met when the direct current and the alternating current voltages are approximately the same and the frequency of the alternating current is not greater than 60 cycles per second.

Universal motors are commonly manufactured in fractional horsepower sizes and are because of their use on either A.C. or D.C. currents, preferred, particularly in areas where power companies supply both types of current.

As previously noted all universal motors are series wound; therefore, their performance characteristics are very much like those of the usual D.C. series motor. The no-load speed is quite high but seldom high enough to damage the motor, as in the case with larger D.C. series motors. When a load is placed on the motor, the speed decreases and continues to decrease as the load increases. Although universal motors of several types of construction are manufactured, they all have the varying speed characteristics just mentioned.

Due to the difficulty in obtaining like performance on A.C. and D.C. at low speeds, most universal motors are designed for operation at speeds of 3,500 *r.p.m.* and higher. Motors operating at load speed of 8,000 to 10,000 *r.p.m.* are common.

Small stationary vacuum cleaners and the larger sizes of portable tools have motors operating at speeds of 3,500 to 8,000 *r.p.m.*

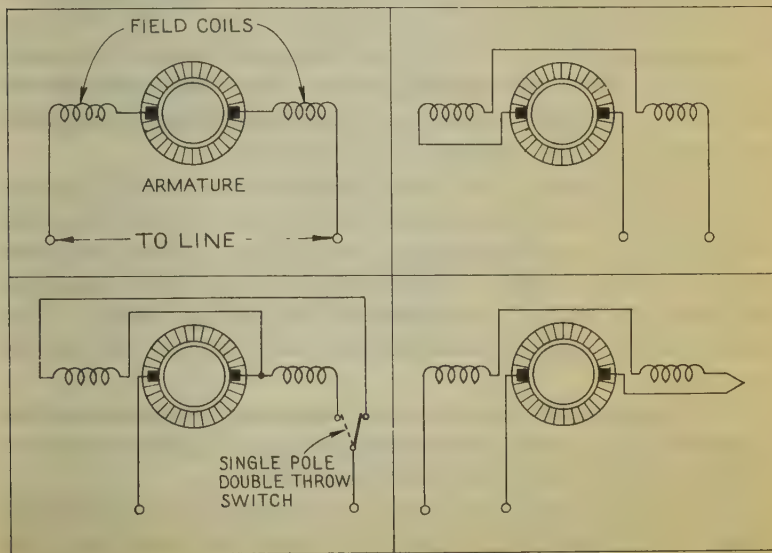
The speed of a universal motor can be adjusted by connecting a resistance of proper value in series with the motor. Advantage of this characteristic is obvious in such application as motor-driven sewing machines, where it is necessary to operate the motor over a large range of speed. In such applications

adjustable resistances are used and the speed is varied at will.

When considering the use of universal motors to drive any apparatus, the following characteristics of the motor will be considered:

1. Change in speed with change in load.
2. Change in speed with change in frequency of power supply.
3. Change in speed due to change in applied voltage.

Since a large percentage of all small motors is connected to lighting circuits where the voltage conditions are not always the best, this last item is of the utmost importance. This con-



Figs. 24 to 27.—Various circuit arrangements for concentrated pole non-compensated Universal motors. Figs. 24 and 25 show connections for non-reversible two-wire motors, whereas figs. 26 and 27 are split-series three- and four-wire reversible motors, respectively.

dition should also be kept in mind when determining the proper motor to use for any application regardless of type. In general, the speed of the universal motor varies with the voltage.

The starting torque of universal motors is usually much more than that required in most applications and does not have to be considered.

Universal motors are manufactured in two general types. They are:

1. Concentrated-pole, non-compensated, and
2. Distributed field compensated.

Most motors of low horsepower rating are of the concentrated pole, non-compensated type, while those of higher ratings are of the distributed-field, compensated type. The dividing line is somewhere near $\frac{1}{4}$ h.p., but the type of motor to be used is determined by the severity of the service and performance required. All of the motors have wound armatures of the same construction as the ordinary D.C. motor.

The concentrated pole, non-compensated motor is exactly the same in construction as a D.C. motor except that the magnetic path is made up of laminations. The laminated stator is made necessary because the magnetic field is alternating when the motor is operated on alternating current. The stator laminations are punched with the poles and the yoke in one piece.

The compensated type of motor has stator laminations of the same shape as those in an induction motor. These motors have stator windings in one of two different types.

The non-compensated motor is simpler and less expensive than the compensated motor and would be used over the entire range of ratings if its performance were as good as that of the compensated motor. The non-compensated type is used

for the higher speeds and lower horsepower ratings only. Figs. 28 and 29 show the speed torque curves for a compensated and non-compensated motor, respectively. It will be noted in fig. 28 that although the rated speed is relatively low for a universal motor, the speed torque curves for various frequencies lie very close together up to 50% above the rated torque load.

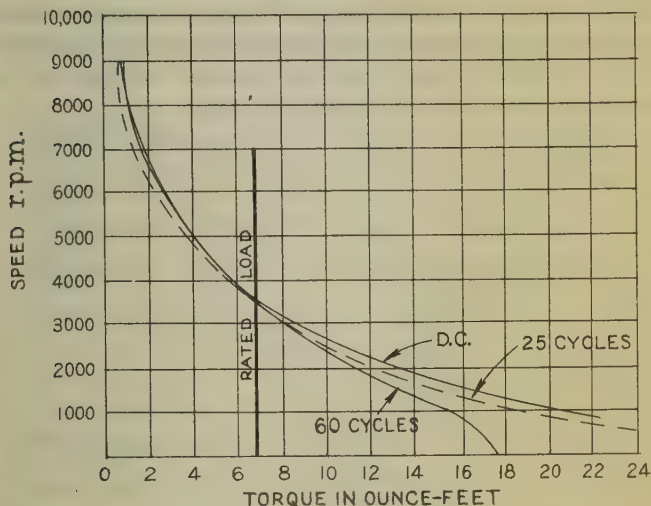


FIG. 28.—Characteristics of a Universal $\frac{1}{4}$ h.p., 3,400 r.p.m. compensated motor.

In fig. 29 the performance of a much higher speed, non-compensated motor is shown. For most universal motor applications the variation in speed at rated loads as shown on this curve is satisfactory. However, the speed curves separate rapidly above full load. If this motor had been designed for lower speed, the tendency of the speed torque curves to separate would have been more pronounced. The chief cause of the

difficulty in keeping the speeds the same is the reactance voltage which exists when the motors are operated on A.C. current. Most of this reactance voltage is produced in the field windings by the main working field. However, in the non-compensated motor some of it is produced in the armature winding by the field produced by the armature ampere turns. The true working voltage is obtained by subtracting the reactance voltage vectorially from the line voltage. If the reactance is high, the performance at a given load will be the same as though there were no reactance voltage and the applied voltage had been reduced with consequent reduction in speed.

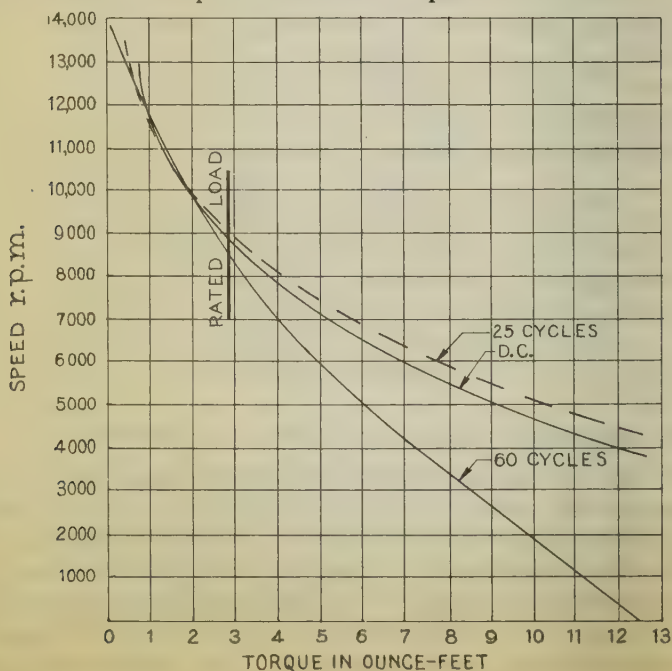


FIG. 29.—Characteristics of a Universal $\frac{1}{4}$ h.p., 8,700 r.p.m. non-compensated motor.

Speed Control Methods

The control method used in single-phase motors, depends upon the type of motor selected for a certain application. Speed control is usually accomplished by means of a centrifugal switch on motors having speeds above 900 r.p.m. A comparison of typical speed-torque characteristics of fractional horsepower single-phase motors is given in fig. 30.

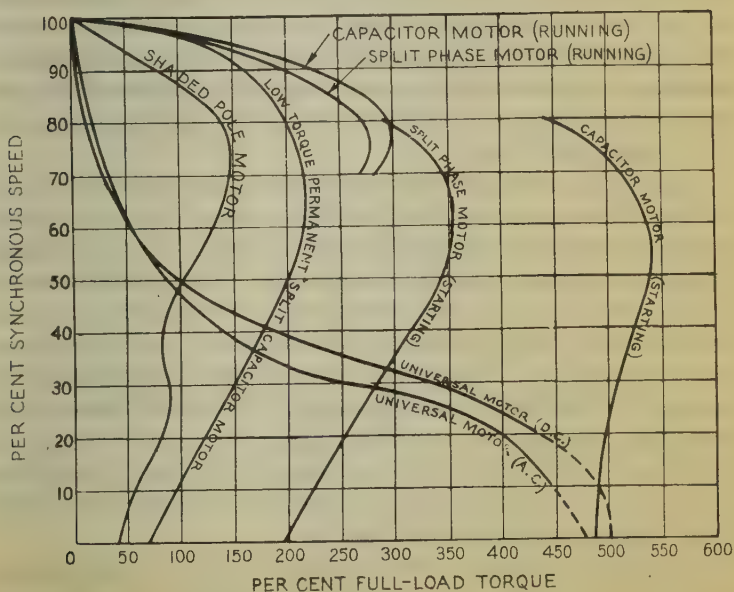


Fig. 30.—Showing speed-torque characteristics of common types fractional horsepower motors.

Where speeds of 900 *r.p.m.* and below are involved, capacitor motors utilizing voltage relays for change-over are preferable to motors using centrifugal switches, because of the sluggishness of a centrifugal switch of normal design at the lower speeds. A voltage relay for change-over is not subject to the same limitations.

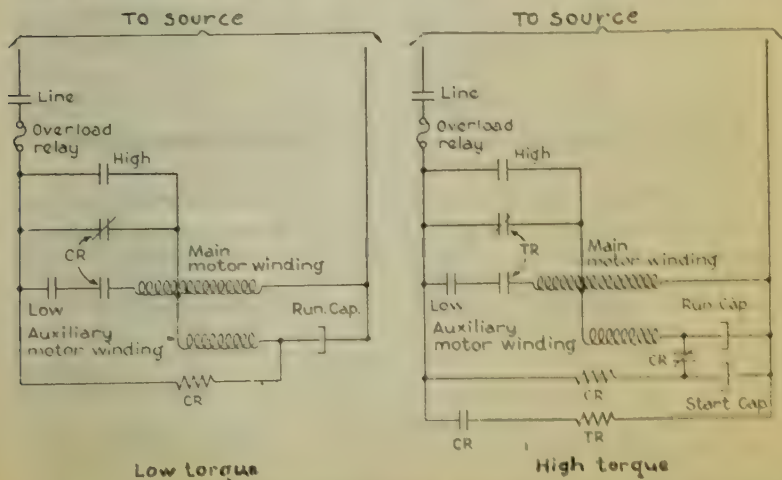
Speed control, because of its more general use, has brought about the standardization of fan speeds permitting the use of high-slip motors. A squirrel-cage motor with 8 to 10% slip and with low maximum torque operates satisfactorily not only for constant-speed drives, but also for adjustable-speed drives through the use of voltage control on the primary winding. Within the working range of a high-slip squirrel-cage motor with adjustable voltage applied to the primary winding, the speed-torque characteristics resemble the characteristics of a wound-rotor motor with different amounts of external resistance in the secondary circuit.

A tapped autotransformer connected to the motor through a multi-position snap switch offers the simplest form of control. The transformer may have a number of taps, only two or three of which are brought out to the switch. This provides two or three speeds, any or all of which may be changed to suit the needs of the application by the proper selection of taps to connect to the switch. Additional contacts on the switch make it a complete starter and speed regulator. Two such transformers connected in open-delta for three-phase, or in each phase of a two-phase circuit may be used to control the speed of polyphase motors. For polyphase use the snap switch must have duplicate contacts for the transformers.

In applying speed control by means of line-voltage adjustment, it must be remembered that the speed of the drive will vary with the load. Therefore, this method of control is not

suitable for centrifugal fans, especially with damper control which affects the fan load. Two-speed pole-changing motors offer a solution for centrifugal fan drives inasmuch as the speed on either pole combination is affected but little by the change in load. Motor speeds in the ratio of 2 to 1 are obtainable as 3,600 1,800 and 1,800 900 *r.p.m.*; 3 to 2 as 1,800 1,200 *r.p.m.*; and 4 to 3 as 1,200 900 *r.p.m.* Other pole combinations are possible.

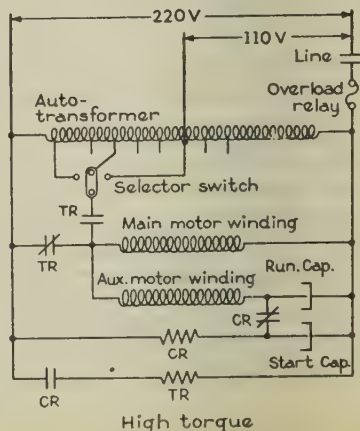
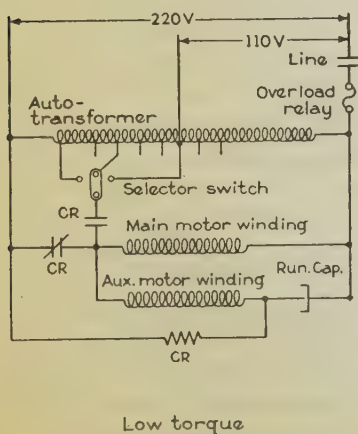
There is still another means of obtaining speed reduction on induction motors. In this the equivalent of building the transformer into the motor is obtained by a suitable tap on the primary winding as shown in figs. 31 and 32. By this means, normal speed and a single reduced speed are provided. A simple pole changing controller is all that is required to complete



FIGS. 31 and 32.—Starting and running circuits of low-torque and high-torque adjustable speed capacitor motors with tapped main winding. In the illustrations, CR represents capacitor relay, actuated by auxiliary motor windings; TR, transfer relay, actuated by capacitor relay.

the installation. Such motors are not generally available, but are provided through propeller fan manufacturers. Each rating is designed for the characteristics of the fan it is to drive and the tap on the winding is located to give the desired low speed.

When speed controllers are used with low-torque capacitor motors, it must be remembered that the available 50% starting torque, with full voltage applied, is reduced in proportion to the square of the voltage involved. The result is low breakaway and low accelerating torque on the low speed setting. In manually operated control, one remedy for this limitation is a progressive starting switch which provides full voltage on the first or high speed position, and reduced voltage on the intermediate and low speed second and third positions, as shown in figs. 33 and 34.



FIGS. 33 and 34.—Showing starting and running circuits of low-torque and high-torque adjustable speed capacitor motors with manually operated transformer speed regulator. In the illustration, CR represents capacitor relay actuated by auxiliary motor winding; TR transfer relay, actuated by capacitor relay.

Where temperature control is used to start and stop the motor, a preset full-voltage starting controller is usually provided. In this case, a relay picking up with the rising voltage of the motor auxiliary winding as it accelerates, operates to disconnect the motor from the direct connection to the line and to connect it to the transformer tap for which the controller is set. In high-torque motors, this relay serves a double purpose of disconnecting the starting capacitor and of changing over from full to reduced voltage on the motor.

Under the general subject of adjustable-speed fan motors, the question of the amount of speed reduction is often debated, and, although it is generally agreed that 30 to 35% speed reduction will meet almost any air conditioning requirement, as much as 50% speed reduction is sometimes specified. In most cases, a lower percentage of speed reduction is found to be acceptable. It is fairly easy to obtain 50% reduction on a fan if the characteristic curve follows the law of horsepower load increasing as the cube of the speed and if the fan fully loads the motor at full speed. It is quite difficult to obtain 50% speed reduction with stability in cases where the drive is 20 to 25% over-motored.

In considering the wide range of air-conditioning equipment from unit heaters and coolers to barn ventilators and incubator ventilating fans, with the many types of equipment between these extremes, the foremost impression is one of economy coupled with simplicity and safety. Simplicity promotes economy. Any additional expense imposed in the interest of safety is abundantly justified from the standpoint of good operating practice. It is not advisable to use a motor of the "long annual service" classification where the operation is infrequent and a motor for short annual service will meet the requirements at a lower first cost with no appreciable increase in operating cost. Similarly, a split-phase motor in fractional horsepower ratings is less expensive than a capacitor motor.

It is essential to avoid misapplications such as low-torque motors on belted drives, or tapped winding and transformer speed control in place of multispeed motors for centrifugal drives; and the drive should be closely motored to give the best results.

Applications

Although single-phase motors are most commonly used in fractional horsepower sizes certain application and power supply conditions make use of single phase motors in integral horsepower sizes.

For extremely small capacities up to $1/40$ *h.p.*, the shaded pole type of motor is most frequently used. This type of motor provides sufficient torque for fans, blowers and other devices and the starting current is not objectionable on lighting lines.

The split-phase motor is the most commonly used in sizes ranging from $1/30$ to $1/2$ *h.p.*, particularly for fan and similar drives where the starting torque is low. In this type of motor a built-in centrifugal switch is usually provided to disconnect the starting-winding as the motor comes up to speed.

In sizes above a $1/4$ *h.p.*, the capacitor motor with 300% starting torque may be used to advantage, especially for pump and compressor drives. It may also be used for fan drives in the lower capacities at higher speeds, in the overlapping ratings; however, it does not offer sufficient advantages over the split-phase motor to warrant its higher cost.

At low speeds (below 900 *r.p.m.*, where centrifugal switches are less successful) and in ratings say from $3/4$ to 3 *h.p.* at all speeds, the capacitor motor finds its widest field of application in fan drives.

The running characteristics of this motor are extremely good and the starting torque is fixed by the amount of additional capacitance added to the auxiliary motor winding during the starting period.

The low torque capacitor motor with no capacitance added to the auxiliary winding during the starting period provides approximately 50% starting torque. This is considered sufficient for directly connected fans, if the unit be one of constant speed or is always started on the high speed position of the starting switch. Where the fan is coupled or belted to the motor the "high torque" type with the additional starting capacitance is preferable.

The change over from "start" to "run" of the high-torque type may be accomplished through the use of a centrifugal switch or by electrical means responsive to current decay or voltage rise as the motor approaches normal running speed.

The repulsion-induction and the repulsion-start induction motors have ratings paralleling those of the capacitor types. These motors have commutators to provide the starting torque. Under normal running conditions, the commutator of the repulsion-start, induction-run type is short circuited, and the motor operates as an induction motor. This differs from the repulsion-induction motor in which the commutator is not short-circuited. A squirrel cage winding deep in the rotor is inactive at starting, but takes up load as the rotor accelerates to full speed, where the normal load is about equally divided between the repulsion and the squirrel cage winding. The starting efficiency of both types is high and the 300% or more starting torque that is available makes them suitable for compressor drives.

The universal type motor on account of its ability to run on direct current as well as on alternating current, is as previously

mentioned preferred on appliances which are required to operate alternately on A.C. and D.C. circuits.

Popular applications for the universal type motor are vacuum cleaners, sewing machines, portable drills, saws, routers, home motion picture projectors and business machines of all kinds.

In this connection, it should be pointed out, that whenever it may become necessary to substitute a motor on any appliance, a good deal of grief and disappointments may be avoided if the identical size and type of motor is reinstalled. Particular attention should be observed with respect to the *name plate data* giving all the necessary information.

A sound rule to follow in this respect is to *copy the entire name plate reading*. This observation holds true irrespective of whether it is a complete motor, or only a spare part is required.

CHAPTER 12

Electrical Instruments

Definitions.—By definition, an *instrument* is a device for measuring the present value of the quantity under observation. An instrument may be an indicating instrument or a recording instrument. An indicating instrument is an instrument in which the present value of the quantity measured is indicated by the position of a pointer relative to a scale.

A recording instrument, on the other hand, is an instrument which makes a graphic record of the value of a quantity under observation as a function of time.

The term *instrument* is used in two different senses, that is (a) the instrument proper, and (b) to include not only the instrument proper, but in addition, any necessary auxiliary devices, such as shunts, shunt leads, resistors, reactors, capacitors or instrument transformers.

The term *meter* is also used in a general sense to designate any type of measuring device including all types of electric measuring instruments, such as voltmeter, ammeter, frequency meter, etc.

Units of Electrical Measure.—The legal units used in electrical measurements are:

1. The ohm.
2. The ampere.
3. The volt.

An *ohm* is the resistance offered to an unvarying electric current by a column of mercury (H_g) at the temperature of melting ice and of uniform cross-section of one square millimeter and a length 106.3 centimeters.

An *ampere* is the unvarying current which when passed through a solution of nitrate of silver in water in accordance with standard specifications, deposits silver at the rate of 1.118 milligrams per second.

A *volt* is the electromotive force (*e.m.f.*) which produces a current of *one ampere* when steadily applied to a conductor whose resistance is *one ohm*.

A *watt* is the power expended when an unvarying electric current of *one ampere* flows through a resistance having a value of *one ohm*.

Classification of Instruments.—The more common electric instruments may be divided roughly into the following classes:

According to the function performed as:

1. Ammeters.
2. Voltmeters.
3. Wattmeters, etc.

According to the circuit on which they are used, as:

1. Alternating current.
2. Direct current.

According to the principle of operation, as:

1. Permanent-magnet moving coil.
2. Dynamometer.
3. Magnetic vane.
4. Induction, etc.

The essential parts of these instruments generally include:

1. Means for providing deflection torque (obtained by interaction of magnetic fields).
2. A spring or other means to provide a counter-torque.
3. A pointer to indicate the resultant position of the instrument moving element.

Direct Current Instruments

Permanent-Magnet Moving Coil Type.—These instruments depend for their operation on the reaction between the current in a movable coil and the field of a fixed permanent magnet.

The essential parts of an instrument of this type are shown in fig. 1.

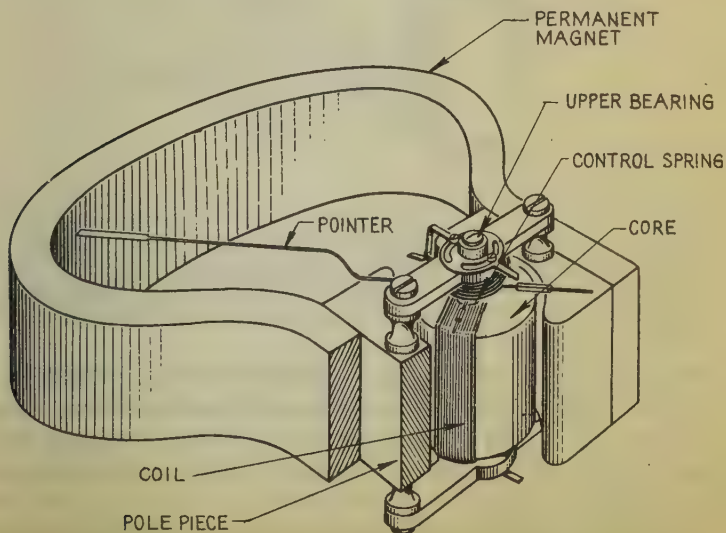
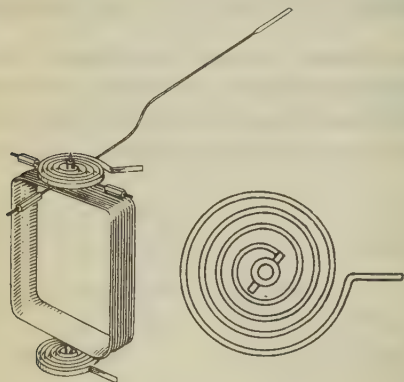


FIG. 1.—Principal parts of a permanent-magnet moving-coil instrument with case removed.

Through pole pieces, the permanent magnet supplies a uniform magnetic field across the air gap, where a moving coil wound with fine wire is located. The moving coil is provided with hardened steel pivots which are so fitted into highly polished jewels that the moving coil can rotate with as little friction as possible.

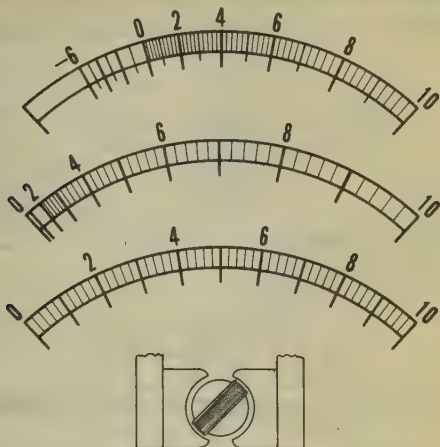


FIGS. 2 and 3.—A typical moving coil for a permanent magnet moving coil system. One spring normally unwinds while the other winds with rotation of the pointer. Both are normally equal in strength and both normally contribute equally in opposing the torque developed by the movement. Each coil carries at top and bottom, a pivot base and a removable pivot. The entire moving system is statically balanced for all positions of the axis by means of three balanced weights.

Springs, made of carefully selected phosphor-bronze strip, are used to lead current into and away from the moving system and also to supply restraining torque. The position of the moving coil is indicated by a pointer which moves over a suitably marked scale.

The entire moving coil assembly is made very light in weight to decrease as far as possible the load on the sharp steel pivots.

In operation, the current through the moving coil provides a field which interacts with the field of the permanent magnet, and thus supplies a deflecting torque.



FIGS. 4 to 7.—Indicating scale forms for various types of measurements. The lower scale is that of the mechanism itself showing linear placement of the divisions with linear increase in current of the moving coil. The center scale shows square law distribution resulting from the use of a heating element with standard mechanism. The top scale shows logarithmic distribution resulting when the permanent-magnet moving coil instrument is used for DB measurements. Because of cramping at the left, the upper two scales are difficult to read at the lower values.

Damping.—Damping is accomplished by winding the moving coil on a light aluminum frame. Eddy currents are set up in the frame because of the motion of the coil in the permanent magnet field. The field produced by the eddy currents interacts with the permanent magnet field in such a manner as to oppose the motion of the coil, thus causing it to come to rest quickly.

Ammeters and Milli-Voltmeters.—In general practice, it is not feasible to send more than 0.1 ampere through the moving coil directly; hence, to accommodate larger currents, shunts are provided as shown in figs. 8 to 10. A shunt for instrument service is usually made from material having a very low temperature co-efficient of resistance and a low thermal *e.m.f.* to copper.

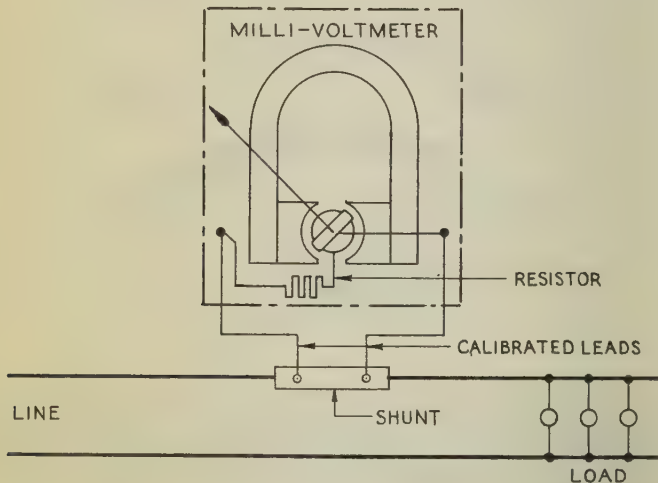
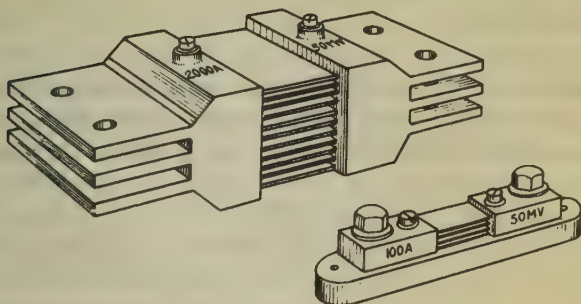


FIG. 8.—Showing milli-voltmeter used for current measurements and connections to shunt.

The low temperature co-efficient of resistance is necessary to assure that the resistance of the shunt, and therefore the instrument indication, will not change when the shunt carries currents which are sufficiently high to cause it to become quite warm. The second requirement, low thermal *e.m.f.* to copper, is important, because, if the shunt terminals become unequally

heated, an appreciable voltage may be superimposed on the normal voltage drop of the shunt and thus cause an appreciable error.



FIGS. 9 and 10.—Showing two types of shunts used for current measurements.

Direct current milli-voltmeters for use with shunts generally require from 10 to 25 milli-amperes at from 30 to 200 milli-volts for full-scale deflection, depending on the class of instrument. One common type of portable instrument requires 25 milli-amperes at 200 milli-volts for full-scale deflection. The corresponding switchboard instruments, which need not be held to such close limits of accuracy, require approximately 50 milli-volts at 20 milli-amperes for full-scale deflection.

It is important to keep in mind that the nominal shunt resistance is the value between the drop terminals; the greater (total) resistance between the current terminals is not ordinarily considered.

It will be noted that the instruments just described are suitable for use only on direct current because the field supplied by

the instrument magnet is uni-directional. Impressing 60 cycle current on such an element will result in a torque pulsation which tends to move the instrument pointer upscale, followed $1/120$ of a second later by a torque pulsation which tends to drive the pointer an equal distance in the opposite direction. Hence, the pointer merely vibrates a small distance about the scale zero point.

Voltmeters.—To make a voltmeter suitable for reading direct current potential, a resistance is inserted in the instrument circuit, as shown in fig. 11. This simply limits the current to

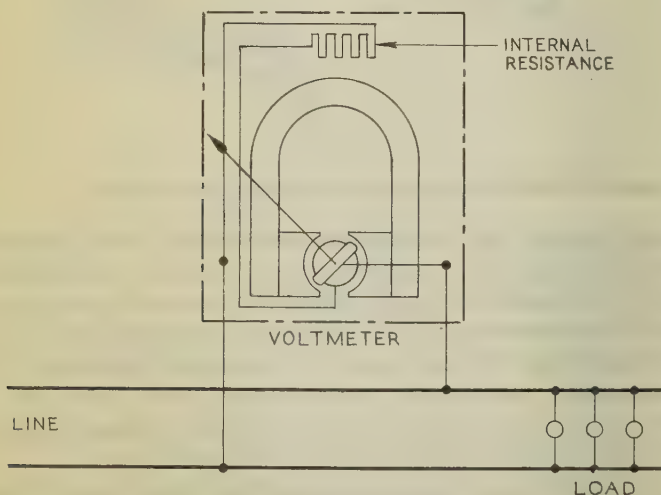


FIG. 11.—Showing voltmeter with internal resistance and connections to line.

such a value that full deflection of the instrument pointer is obtained when the maximum voltage which it is desired to read is applied to the instrument. For example, if an ammeter

rated 10 milli-amperes (0.01 ampere) full scale and it is required to make it a voltmeter having a full scale rating of 150 volts, it would require a total resistance of $150/0.01 = 15,000$ ohms.

The milli-ammeter moving coil itself, of course, has some resistance, about 20 ohms; so only 14,980 ohms resistance need be added. This resistor is made of very stable material which is not affected by ordinary changes in temperature. The amount of constant resistance added is sufficient to compensate the effect of moving system resistance which changes with temperature. Hence, the same current will always flow through the element when a given voltage is applied, regardless of the temperature at which the instrument operates. Several different ranges are obtained by using separate tapped resistors known as multipliers, fig. 12, or by tapping off various points on the same resistor as shown in fig. 13.

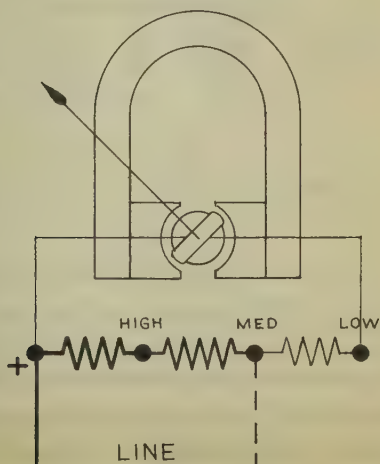


FIG. 12.—Showing resistor arrangement for various ranges of voltage.

It is possible to make voltmeters that require a very small amount of current for their operation. A common type of portable instrument, rated at 150 volts, requires about 10 milli-amperes for full-scale deflection. It is customary to refer to direct current voltmeters as possessing a certain number of ohms per volt.

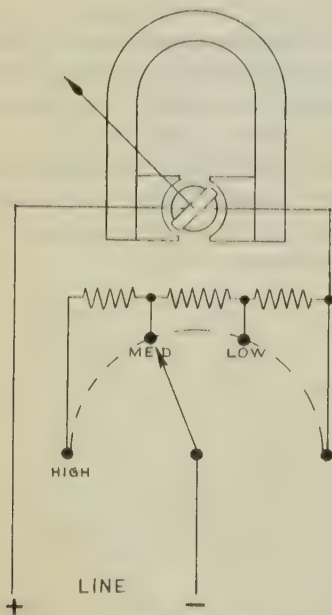


FIG. 13.—Arrangement of voltmeter resistor with resistors tapped for switch selection.

For example, the 150 volt voltmeter just mentioned requires 10 milli-amperes for full-scale deflection. Hence, its resistance must be 15,000 ohms. Since the resistance is 15,000 ohms and the full-scale volts are 150, the instrument has $15,000/150$ or

100 ohms per volt. Other portable voltmeters can be made which are considerably more sensitive. Some types on the market possess a resistance as high as 10,000 ohms per volt.

Effect of Direct Current Instruments on Circuit.—At this point, it is well to study the effect on readings which is caused by the current taken by an instrument. For example, if a large generator, as shown in fig. 14, is capable of delivering a large amount of power at 150 volts, the voltage drop in the source (due to the 10 milli-ampere current drain of a 15,000 ohms, 150 volt voltmeter) will be entirely negligible. Hence, such a voltmeter is entirely satisfactory for such measurements.

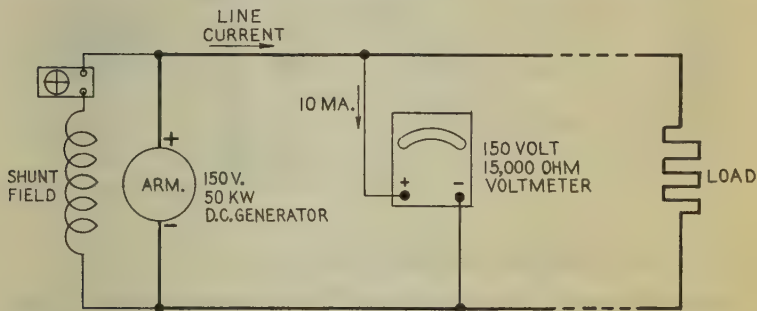


FIG. 14.—Showing voltmeter connections to large direct current generator.

However, going to the other extreme, if a radio power unit, as shown in fig. 15, delivers 150 volts, it may be found that this power unit has an internal resistance as high as 1,000 ohms. If the 150 volt voltmeter be connected to the output of this unit, the true value of the open circuit voltage will not be read, since the total resistance through which the current has to flow will be 16,000 ohms applied across 150 volts, and the cur-

rent will be $150/(15,000 + 1,000)$ or 9.375 milli-amperes, and the instrument will read 150 ($0.009375/0.010$) or 140.6 volts on scale.

On the other hand, suppose a 150 volt voltmeter be used requiring only 1 milli-ampere for full-scale deflection. This instrument has a resistance of 1,000 ohms per volt, and when connected to the power unit, the current flowing in the circuit would be $150/151,000$ or 0.993 milli-ampere.

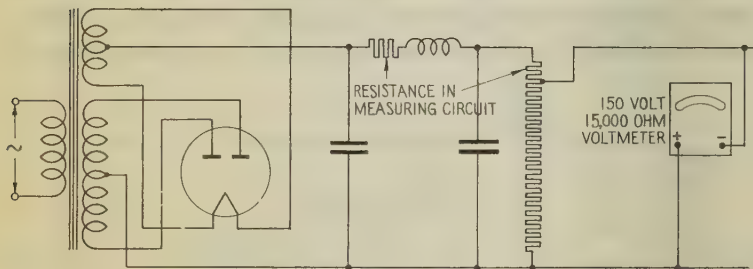


FIG. 15.—Showing voltmeter connections to typical radio power unit.

The instrument will then read $150 (0.000993/0.001) = 149$ volts, on scale. In other words, to determine the open circuit voltage of the power unit, using an ordinary 100 ohms per volt instrument for its measure, there would be an error of 9.4 volts, while the 1,000 ohms per volt instrument would read the correct value to within 1 volt. The foregoing does not take into account the lowered voltage of the power transformer caused by the load imposed by the voltmeter.

With this in mind, it is well to consider the effects which occur when ammeters are connected in circuits. When the circuit is of reasonably high voltage, so that the 50, 100 or 200

milli-volts representing the drop across the ammeter shunt are an inconsequential portion of the total line voltage, introduction of a direct current ammeter will have only a negligible effect. For example, if it be desired to measure the current in a 150 volt, 0.3 ohm circuit, as shown in fig. 16, connect a 500 ampere direct current ammeter in the line as shown. Before the ammeter was inserted in the circuit, the line current was $150/0.300$ or 500 amperes.

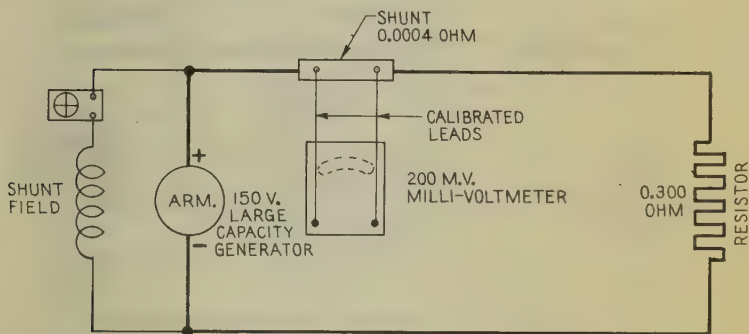


FIG. 16.—Showing ammeter connections to medium voltage circuit.

If the 500 ampere shunt was rated 200 milli-volts at full load, this would mean that its resistance is $0.2/500$ or 0.0004 ohm (neglecting shunt terminal resistance). When the shunt is inserted in the circuit, the current which will flow is reduced to $150/0.3004$ or 499.3 amperes. This is sufficiently close to the true value so that the effect of the introduction of the ammeter shunt can be entirely disregarded.

On the other hand, suppose a 6 volt source, such as a storage battery, furnishes current to a resistance of 0.012 ohm, as shown

in fig. 17. Without any ammeter shunt in circuit, the line current is $6/0.012 = 500$ amperes. With the ammeter shunt in the circuit, the current is altered to $6/(0.012 + 0.0004) = 483.9$ amperes. This value, as indicated by the ammeter, compared with the original value of 500 amperes, is sufficient to warrant consideration. In such cases, the resistance of the leads used to connect the shunt in the circuit must also be considered.

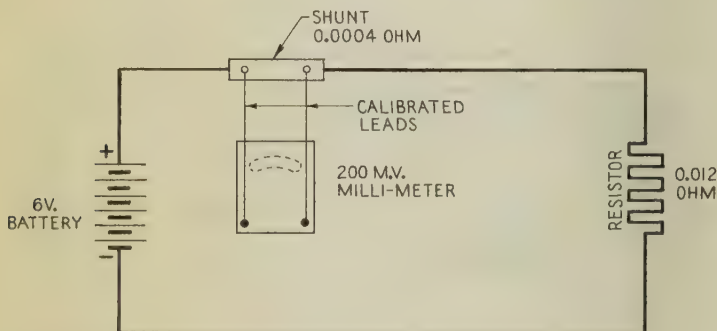


FIG. 17.—Ammeter connections to low voltage source.

Alternating-Current Instruments

Dynamometer Type.—The previously described instruments are suitable for measurements of direct current only, because the field supplied by the permanent magnet is uni-directional. If, however, the permanent magnet be removed and replaced with stationary coils arranged as shown in fig. 18, and the moving and stationary coils be connected in series, the moving coil will be deflected by an alternating current.

This deflection is obtained because when the alternating current reverses, the current of the fixed and moving coils reverses at the same instant, thus a pulsating torque is obtained, which is always in the same direction.

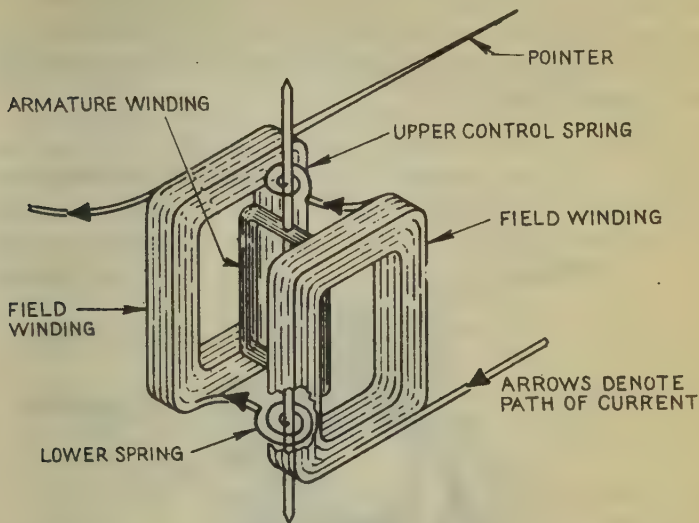


FIG. 18.—Schematic illustration showing arrangements of coils in dynamometer type of instrument.

The amount of deflection bears a direct relationship to the amount of alternating current sent through the coil system. It is this method of arrangement which is the basis for the modern dynamometer instrument illustrated in fig. 19.

Irrespective of the degree of refinement used in construction of this instrument, it takes a considerably larger amount of current than the permanent magnet type of instrument employed for direct current measurement. Here the current being measured must not only supply the energy for the moving coil, but must also supply energy for the field winding, which in

the case of the permanent magnet instrument was supplied by the magnet.

Another important consideration in connection with this type of instrument is to keep masses of metals as well as closed loops of wire away from the instrument coil system.

Any such material would form a path in which current would be induced, thus causing reading errors when used in alternating current measurement.

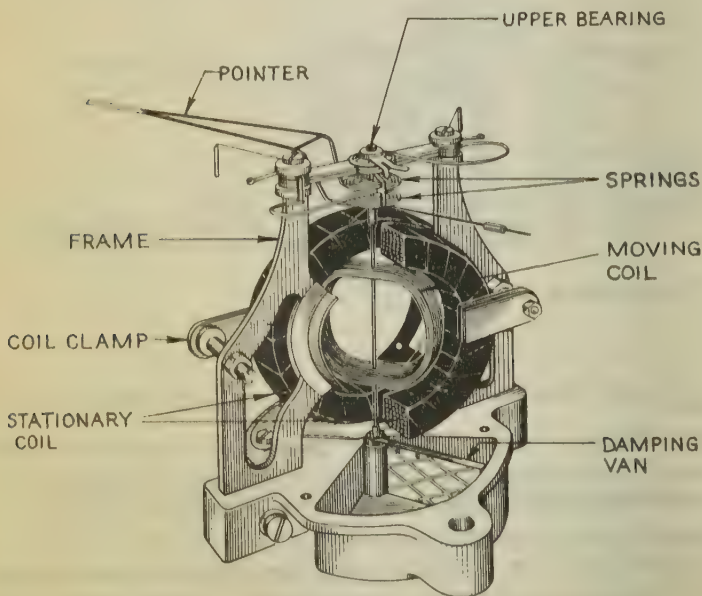


FIG. 19.—Showing principal parts of modern dynamometer mechanism. These mechanisms are the most fundamental of all the indicating devices now used. Form factor variations do not occur because of the complete absence of magnetic materials such as iron and the indications are of true *r.m.s.* (root mean square) values.

Dynamometer Instrument Damping.—Because of the oscillating effect of the alternating current on the instrument pointer, the instrument is equipped with a damper.

This damping is accomplished in two ways: (a) By the use of a thin aluminum or copper vane which swings between the poles of a permanent magnet, and (b) by the use of a closed box in which a vane swings in a restricted space.

This latter method of damping is called air damping, while the former is called magnetic damping. Both methods are in common use, although it is considerably easier to obtain high values of damping by the magnetic method. Figs 20 and 21 show a schematic diagram of the magnetic and air types, respectively.

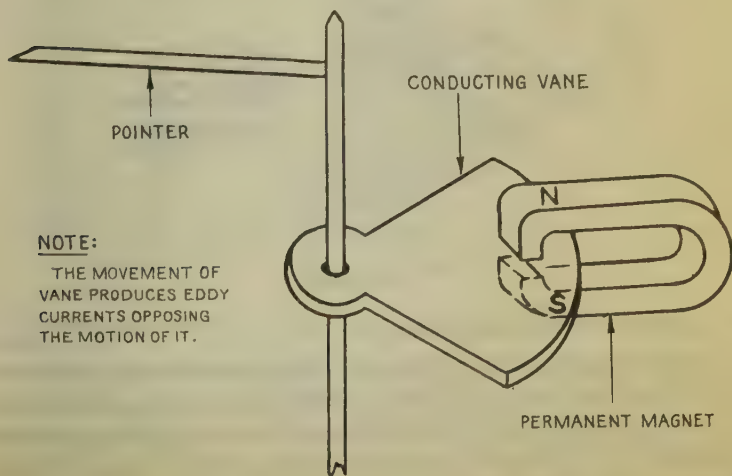


FIG. 20.—Showing details of magnetic-damping mechanism.

Voltmeters.—If to the dynamometer-type (alternating current) milli-ammeter described previously, suitable series resistance constructed of zero-temperature co-efficient material be added, as shown in fig. 22, a voltmeter which can be used to measure alternating current volts is obtained.

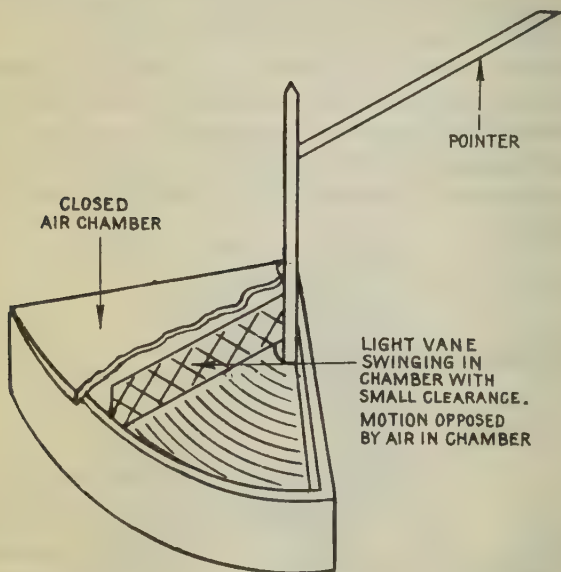


FIG. 21.—Details of air-damping mechanism.

Alternating current voltmeters draw considerably more current from the line than direct current voltmeters. In fact, it is not unusual to have a high grade portable alternating current voltmeter of 150 volt rating require as much as 75 milliamperes for full-scale deflection. This gives an instrument resistance of approximately 2,000 ohms and a full-scale power consumption of about 11 watts.

The series resistor of fig. 22 contributes nothing to the torque of the instrument, since torque is governed by the product of the ampere turns of the fixed and moving coils. If the fixed and moving coils be wound entirely of resistance wire, the fixed resistor normally used could be dispensed with. This, however, is not practical, because of the large amount of heat which would then have to be dissipated by the coil system.

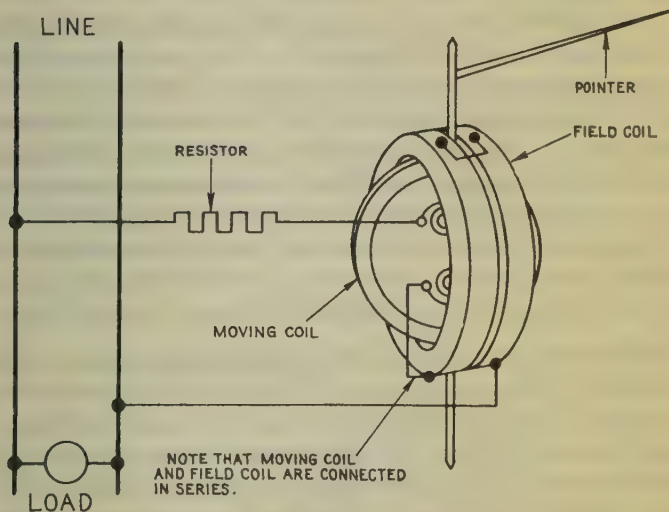


FIG. 22.—Schematic arrangement of dynamometer element when used for measurements of voltage.

To obviate this difficulty, the fixed and moving coils are wound with copper wire. Then to reduce the instrument error caused by change in the resistance of copper when the temperature is varied, it is customary to mask or "swamp out" the error by using sufficient series resistance of negligible temperature co-efficient. It has been found that a satisfactory relation

between copper resistance and swamping resistance exists when the copper resistance amounts to about 10% of the total resistance of the instrument.

In other words, in the 150 volt portable instrument previously described, the field and moving coils would have a combined resistance of about 200 ohms, and the series resistance would be approximately 1,800 ohms, making a total of 2,000 ohms.

If the full-scale voltage rating of the instrument be lowered, the resistance of the instrument, of course, must decrease. Also, it is necessary to keep the copper resistance at about the same proportion, namely 10%. This limits the number of turns which it is possible to wind on the fixed and moving coils. Hence, to get the same torque in the instrument, more current must be used, which means that the instrument may draw a very appreciable current from the line. For example, a 15 volt alternating current instrument of the higher grade portable type may draw as much as 250 milli-amperes from the line.

To illustrate the effect of increasing the percentage of copper resistance, an instrument could be made which would require less current for full-scale deflection by using smaller size copper wire on the fixed and moving coils, and by increasing the number of turns. However, the performance of the instrument under various conditions of ambient temperature might be quite poor.

Suppose that instead of using 10% or 6 ohms of copper in a 15 volt, 60 ohm instrument, 30 ohms copper and 30 ohms zero temperature co-efficient resistance be used. Copper changes 0.4% for each degree C. change in ambient temperature; thus, if the temperature at which the instrument is used were increased 10°, the resistance of the copper circuit would increase to 31.2 ohms, giving an instrument resistance of 61.2 ohms

at this temperature. The instrument would then read 60/61.2 or only 98% of the correct value when 15 volts were applied.

The foregoing assumption as to instrument indication does not take into account the change in elastic modulus of the instrument spring at this higher temperature. As a matter of fact, in most instruments, the elastic properties of phosphor-bronze spring material change in such a direction as to compensate partly for the error in indication caused by change in the copper resistance of the instrument.

Ammeters.—Instead of changing the milli-ammeter into a voltmeter by providing it with a series resistance, if it be equipped with a shunt, it could be used for measuring values of alternating current greater than 100 milli-amperes. However, there would be some practical difficulties in applying this scheme if the shunt be used, as shown in fig. 23.

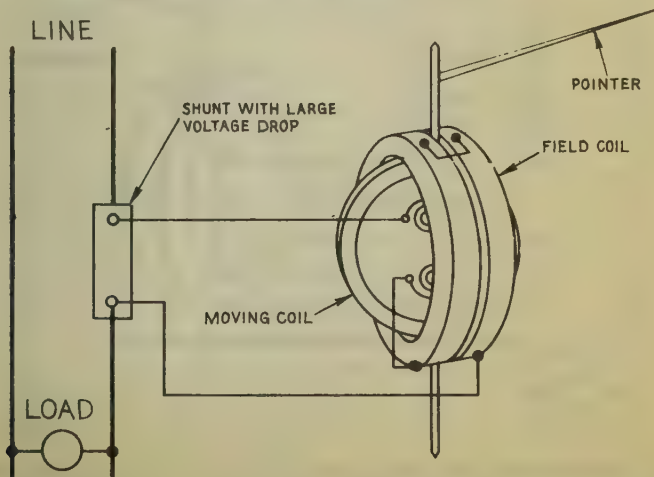


FIG. 23.—Illustrating how a dynamometer may be used to measure a current of several amperes.

The shunt would require to have a very high voltage drop at rated current to divert sufficient current through the ammeter element to obtain full-scale deflection. The milli-ammeter element would also have to consist principally of copper. As the ambient temperature increases, the amount of current flowing in the instrument element for any given line current would be lower. The inductance of the coils must also be considered.

In order to overcome these difficulties, it is customary to send the full line current through the fixed coils of a dynamometer-ammeter, and to allow only the current for the moving element to be taken off the shunt, as shown in fig. 24. This arrangement permits the use of some series resistance, and materially

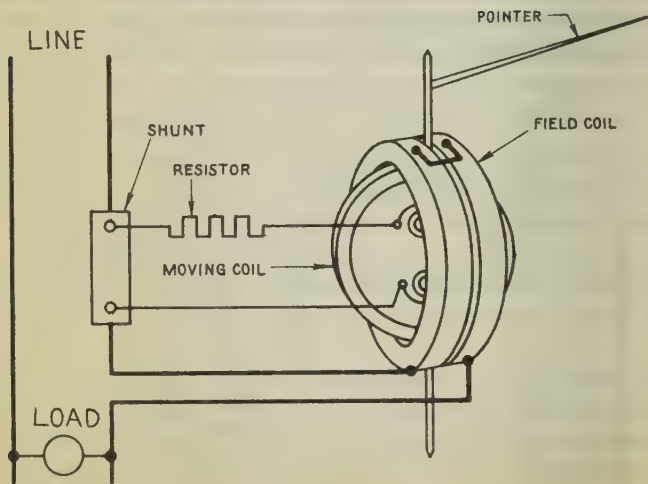


FIG. 24.—Showing modern method of using a dynamometer element for measurement of current values. Here the field coil carries all of the line current, whereas the moving coil carries a definite fraction thereof.

improves both the temperature co-efficient and the time constant of the instrument. For the lower ratings, the shunt can be located within the instrument case.

Wattmeters.—Assume the ammeter arrangement shown in fig. 24, be connected in a circuit, as shown in fig. 25, omitting the shunt and adding resistance in series with the moving element instead. On alternating current, the deflection of the instrument pointer would depend on the product of the instantaneous current flowing in the fixed and moving coils.

Since the current in the moving element is proportional to the line voltage, the instrument indication will be proportional to the product of the instantaneous voltage times the instantaneous line current. In other words, the instrument will read watts, and the scale can be so marked.

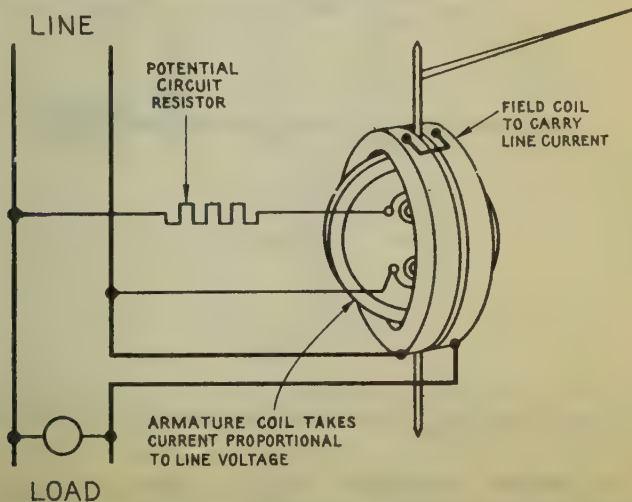


FIG. 25.—Elementary view of dynamometer element arranged to measure power consumption in watts of the load.

If the maximum and other corresponding values of current and voltage occur at the same instant, as shown in fig. 26, that is, if the angle between them be zero, the load is said to have a power factor of unity, since cosine ϕ (ϕ is the angle between current and voltage) is equal to 1. If the current lag 30° behind the voltage, as shown in fig. 27, the power factor is 0.866 lagging.

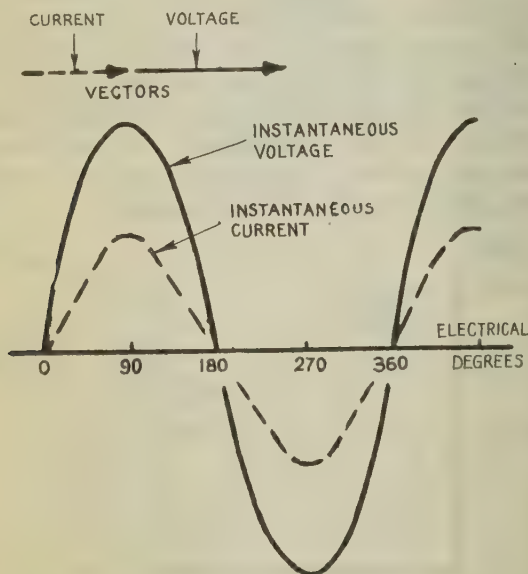


FIG. 26.—Showing current and voltage relations in an alternating current circuit when the power factor of the circuit equals 1.

Note how the instrument which is shown in fig. 25 will respond to this condition, remembering that it always reads the quantity proportional to the instantaneous product of the volts

and amperes. To take a specific example: Draw lines corresponding to the voltage and current, values e and i , at a given instant, t , as shown in figs. 28 and 29 and take their product. This product ($e \times i$ in fig. 30) will be indicative of the torque on the moving element at that particular instant. Repeating this at suitable intervals, a torque curve which approximates that shown in fig. 30 will be obtained.

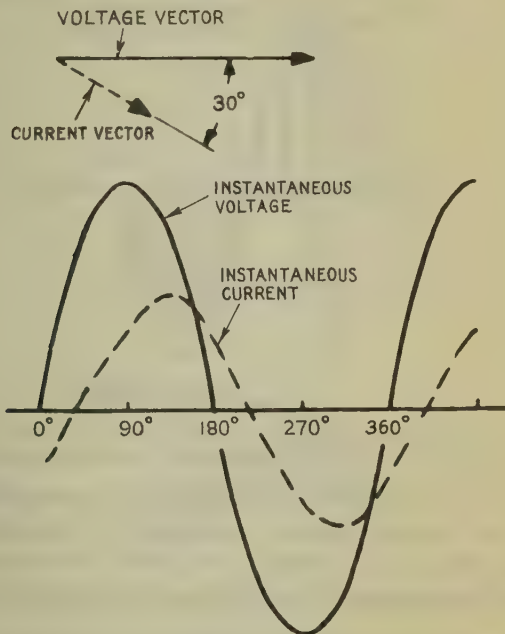
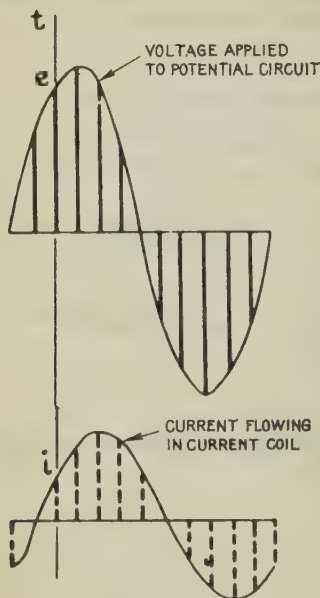


FIG. 27.—Illustrating current and voltage relations with current lagging the voltage at an angle of 30° .

Note that the torque is positive in direction at certain intervals during the cycle, and negative in others. The instrument pointer will, of course, assume a position dependent on the

average value of the torque over a period of time, since the instrument element is not light enough to respond to each impulse of a 60 cycle source. Had a power factor of unity been selected, the torque would have been positive in direction at each instant.



FIGS. 28 and 29.—Showing current and voltage relations in a wattmeter.

While pursuing this analysis, apply it to the voltmeter which would be connected across the same line, plotting the torque curve over one cycle. Since, in a voltmeter such as is indicated in fig. 22, the field and moving coils are connected in series, the instantaneous currents in each element are always in phase, regardless of the power factor of the line.

To obtain the torque curve, simply square the ordinates on the current curve. Because of the mass of the moving element, the instrument pointer will again assume an average position with respect to the double frequency torque pulsations. These conditions and the procedure are indicated in figs. 31 to 33.

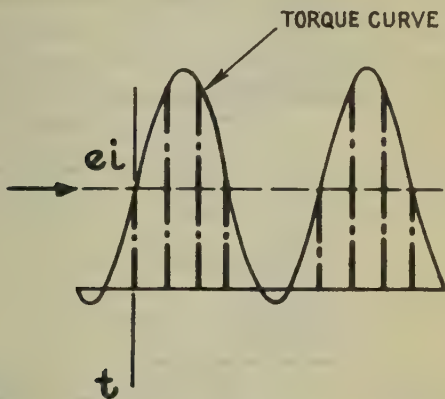


FIG. 30.—Torque curve obtained as product of current and potential circuit, figs. 28 and 29. It should be noted that torque on wattmeter element reverses in direction during each cycle.

The dynamometer-ammeter element shown in fig. 25 will also be subjected to the same continuous positive pulsating torque, since the current in the movable coil is always in phase with the line current which flows in the current coil.

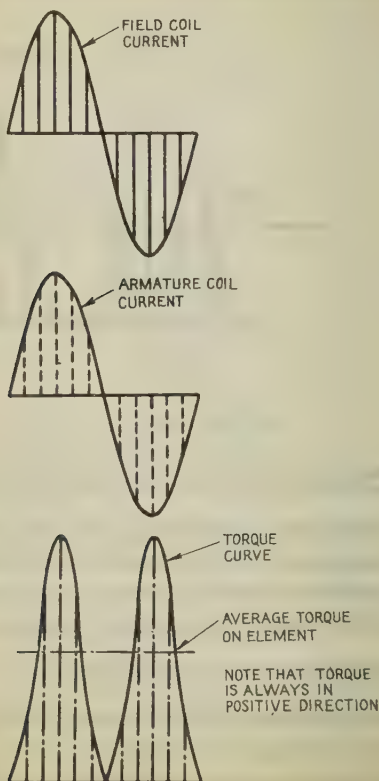
It should always be remembered that:

The dynamometer-volt meter indicates *root-mean-square* (*r.m.s.*) voltage.

The dynamometer-ammeter indicates *root-mean-square* (*r.m.s.*) current.

The dynamometer-wattmeter indicates *average* power.

A wattmeter may be connected in circuit as shown in fig. 34 or as in fig. 35. Note that in one case the wattmeter potential-circuit loss is being measured; and in the other, the wattmeter current-coil loss.



FIGS. 31 TO 33.—Showing field, armature and torque curves as obtained by wattmeter measurements.

The potential circuit loss of a typical portable 500 watt wattmeter, 5 amperes, 100 volts, would be in the order of 2 watts at 100 volts; hence, if this instrument were connected as shown in fig. 34 the watt reading would be 2 watts higher than the true value of watts consumed in the load. The current coil for the wattmeter previously described, requires about 2 watts at about 5 amperes. Since the voltage is usually fairly constant, while the current varies, it is much easier to correct the readings for a constant potential circuit loss than for a varying current coil loss. Thus, the connection including the potential-circuit loss is usually preferred.

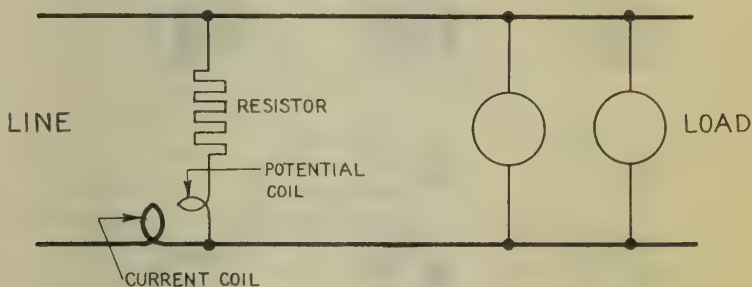


FIG. 34.—Illustrating connection of wattmeter element with wattmeter current coil connected ahead of the potential coil.

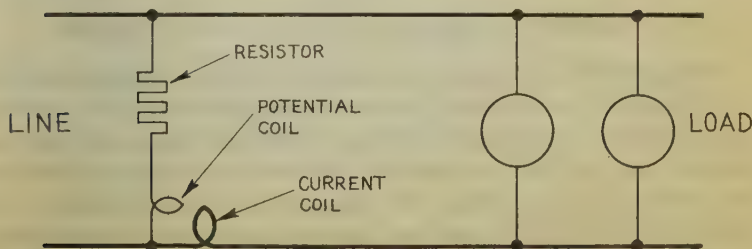
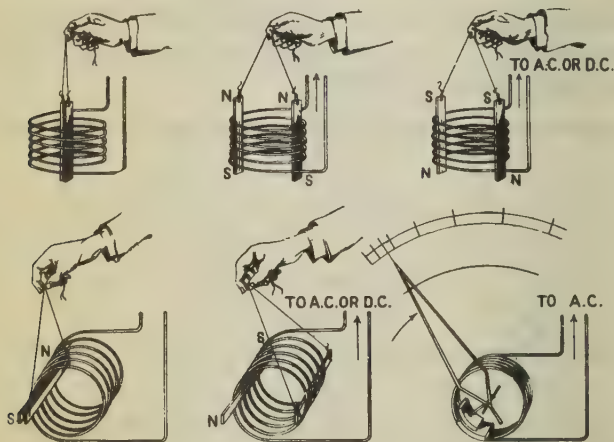


FIG. 35.—Showing wattmeter potential coil element connected ahead of its current coil.

Magnetic-Vane Type.—This alternating current instrument, sometimes termed moving-iron instrument or moving-iron vane instrument, is often used for ammeters and voltmeters. The instrument depends for its operation upon the reactions resulting from the current in one or more fixed coils acting upon one or more pieces of soft iron or magnetically similar material in the moving system. The moving iron principle is illustrated in figs. 36 to 41.



FIGS. 36 TO 41.—Illustrating working principles of the magnetic-vane type instrument.

If two similar adjacent iron bars are similarly magnetized, a repelling force is developed between them which tends to move them apart. In the moving iron instrument this principle is used by one bar fixed in space and pivoting the second so that it will tend to rotate when the magnetizing current flows. A spring attached to the moving vane opposes the motion of the vane and permits the scale to be calibrated in terms of the current flowing.

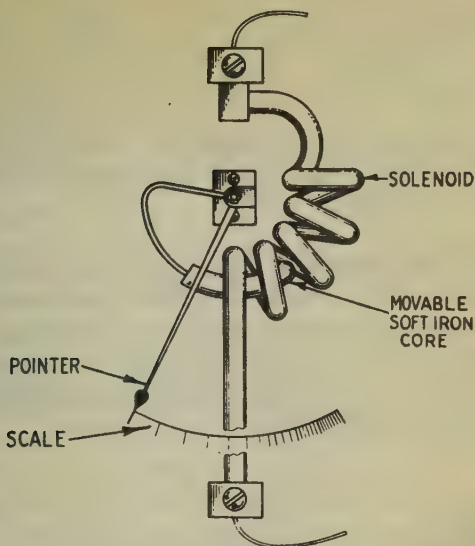
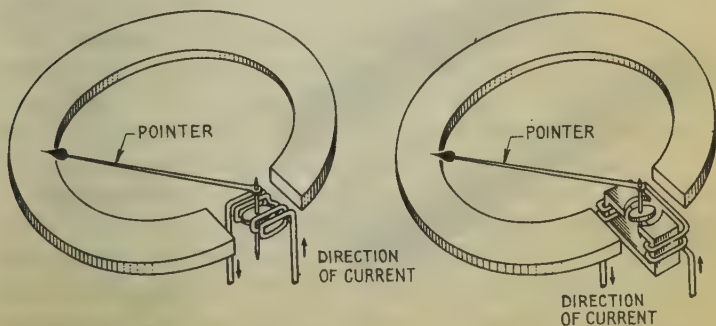


FIG. 42.—Principal parts of simple magnetic-vane attraction type instrument.



FIGS. 43 and 44.—Polarized iron-vane mechanisms. In fig. 43 the pointer is driven by an iron vane governed by the resultant field of the permanent magnet and that of the current in the coil. If a soft iron core be added as in fig. 44, the sensitivity of the instrument as well as the scale characteristics will be greatly improved.

When the current is sent through the solenoid, the plunger is drawn into the coil, and a measurable deflection of the instrument pointer is obtained. Due, however, to high power consumption, sensitivity to slight zero shifts, scale difficulties, etc., this instrument is presently used only in less expensive types. Other simple polarized iron vane instrument mechanisms are shown in figs. 43 and 44.

Magnetic-Vane Repulsion Type.—This instrument, fig. 45, differs in construction principles from the previously described moving iron vane instrument in that the magnetic vane embedded in the side of the coil will have definite poles N-S at the points shown. The moving vane will also be magnetized by induction, the polarities being N-S as shown.

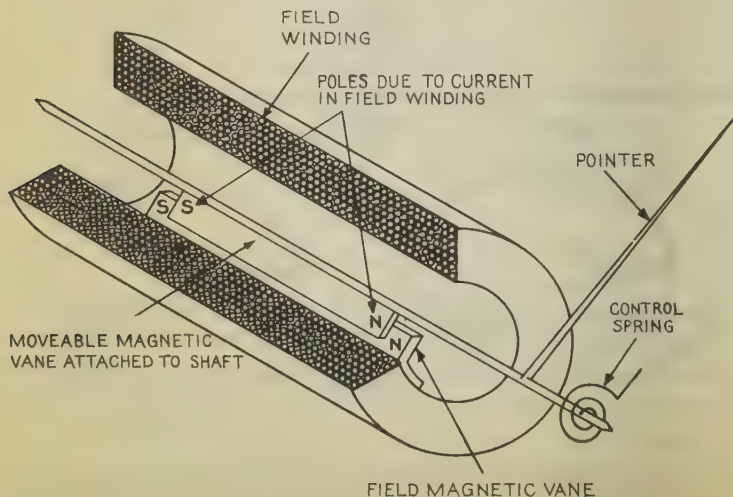


FIG. 45.—Schematic illustration of simple magnetic-vane repulsion type instrument.

It will be noted that the north pole of the moving vane is nearest to the north pole on the piece of magnetic material embedded in the coil, and the south poles are similarly placed. Hence, the vane tends to move away or to be repelled from the stationary magnetic piece.

If alternating current is applied to the instrument, the two vanes will simultaneously change polarities as the current varies throughout the cycle; thus the instrument also operates on alternating current. In fact, it is in alternating current measurements that the instrument finds its greatest application.

Induction Type.—This type of instrument depends for its operation upon the reactions between a magnetic flux (or fluxes) set up by one or more currents in fixed windings, and electric currents set up by electromagnetic induction in conducting parts of the moving system.

The construction of a typical induction instrument is shown in fig. 46. The instrument consists primarily of a field structure with associated windings into which a rotating disc of aluminum is placed.

The disc will tend to rotate when an alternating current of the proper phase relation is applied to the two coils. If a spring be inserted on the disc shaft to counteract the movement of the disc, and a pointer be added, its movement will indicate the value of the current flowing through the instrument.

This instrument of course can be used on alternating current only. If a direct current were applied, the only time at which voltage would be induced in the disc would be just when the circuit was opened or closed. Thus, the disc will tend to move forward and then drop back to its initial position when a steady-state condition is reached.

The disc must be made of aluminum or copper, or of some other material of high electrical conductivity. Since all these materials possess appreciable temperature co-efficients of resistance, changes in temperature will affect the readings materially, unless carefully compensated for in other parts of the circuit. This has limited the usefulness of these devices as instruments to a considerable extent.

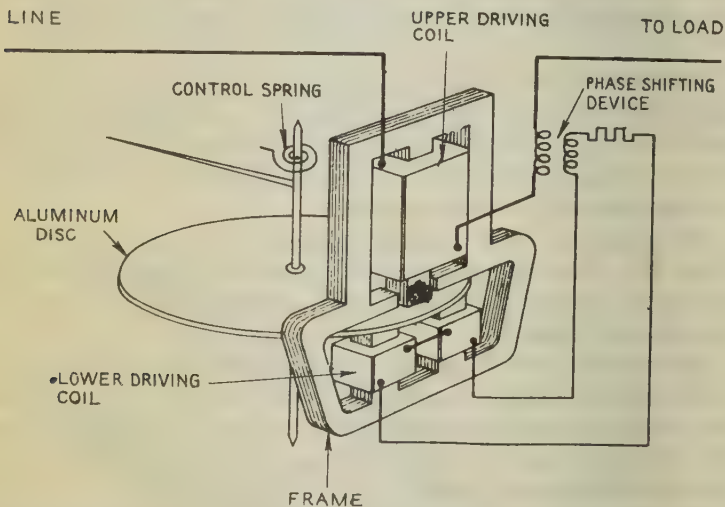


Fig. 46.—Schematic illustration of an induction type instrument.

Induction Watt-Hour Meter.—If in a structure such as shown in fig. 46, the spring and pointer be omitted and magnets be placed at the edge of the disc as shown in fig. 47, the disc will tend to rotate due to the action of the current in the field structure as before. The disc will cut lines of magnetic flux from

the magnets located at its periphery, and the currents induced will tend to reduce the speed of the disc.

The effect of temperature on such an arrangement is not nearly so pronounced as in the case of the spring controlled induction instrument. As the temperature increases, both the induced current actuating the disc and the eddy currents caused by the damping magnets tend to decrease in the same proportion.

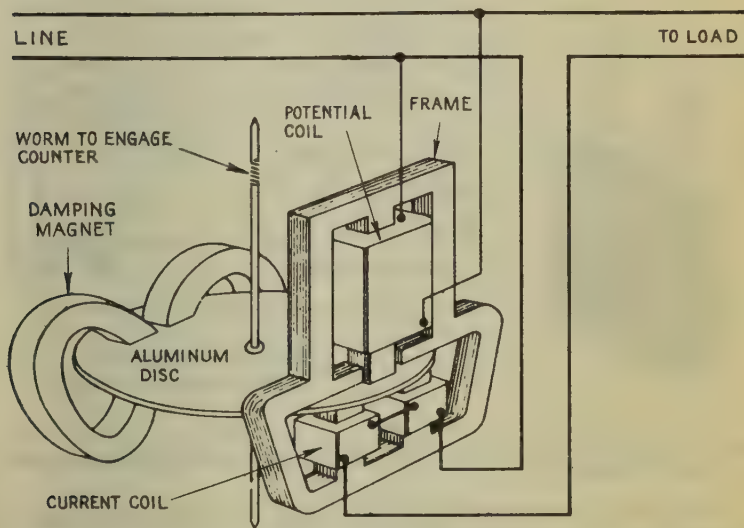
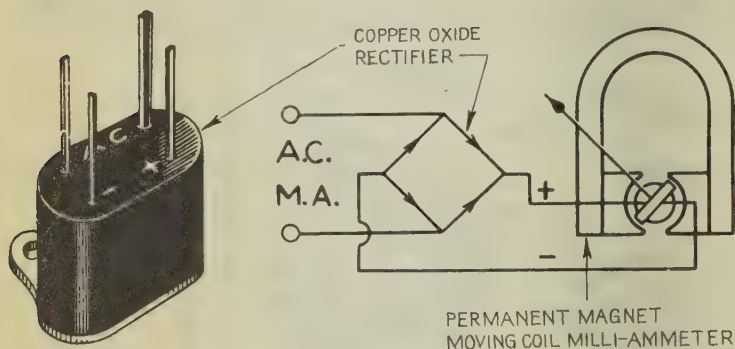


FIG. 47.—Showing induction type instrument used as watt-hour meter. Here the initial phase shift between flux of current and potential coils is produced by making potential coil consist mainly of reactance and the current coil mainly of resistance.

If the connections be changed and a counter added, connected by suitable gearing, to count the total revolutions of the disc of the device shown in fig. 47, the basic elements of the induction watt hour meter are obtained.

Rectifier Type Instruments.—Principally a rectifier instrument is the combination of an instrument sensitive to direct current and a rectifying device whereby alternating currents or voltages may be measured.

By inserting a rectifier in the alternating current circuit as shown in fig. 49, it will be possible to use the previously described permanent magnet moving coil type of instrument to measure the value of an alternating current.



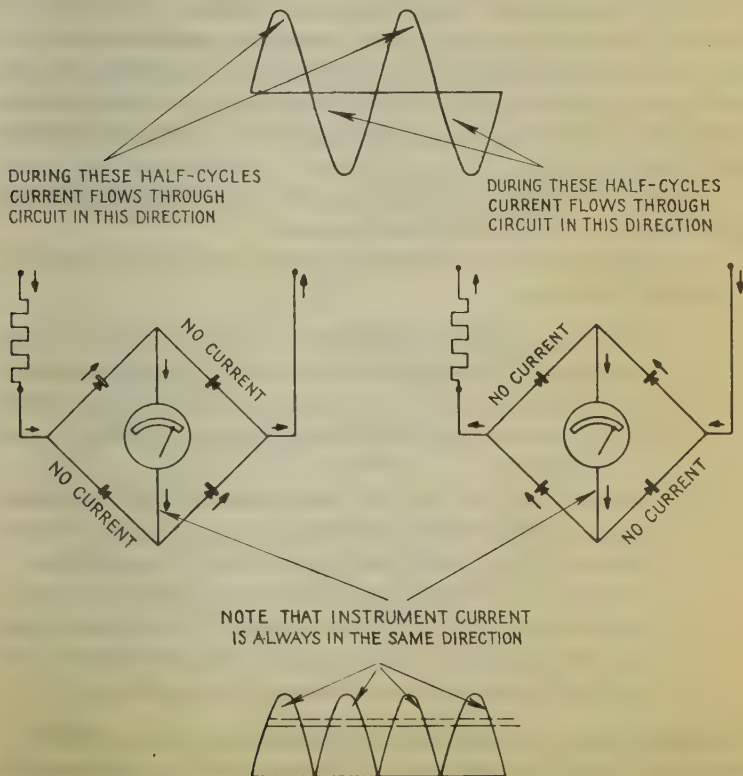
FIGS. 48 and 49.—Typical rectifier and circuit connection when used with permanent-magnet moving coil instrument.

A rectifier instrument may be equipped with any one of several types of rectifying devices. The one most commonly used is the copper-oxide type, which works on the principle that the electrical resistance of a properly formed layer of copper oxide on a copper surface depends upon the polarity of the applied voltage.

The most common method used is to arrange four copper plates in a bridge connection as shown in figs. 51 and 52. This

bridge arrangement rectifies every half-cycle of the A.C. wave and is called a full-wave rectifier.

When using rectifier instruments, it should always be borne in mind what the instrument really indicates, regardless of how the scale may be marked. A permanent magnet moving coil type instrument indicates average values, and with the rectified sine wave shown in fig. 53 the average value is shown by the



FIGS. 50 to 53.—Illustrating working principles of rectifier type instrument.

lower line. On alternating current circuits, however, the root mean square (*r.m.s.*) value is the quantity generally required. In fig. 53 this is shown by the higher line.

For a sine wave, the ratio $\frac{\text{r.m.s. value}}{\text{average value}} = 1.11$ and the in-

strument scale is marked directly in terms of the *r.m.s.* value. For other wave shapes, this ratio is different, and hence, a rectifier instrument reads *r.m.s.* quantities correctly only on the wave shape for which it is calibrated. This point must be kept in mind when using rectifier instruments to measure non-sinusoidal quantities, such as the outputs of constant voltage transformers.

Fortunately, the errors resulting from this condition are generally less than 10% of full scale value.

Some other points to be kept in mind when using rectifier-type instruments are:

- (a) Some aging of the rectifiers occurs in service. For this reason, the stated accuracy of rectifier instruments is often given as $\pm 5\%$ of full scale. Consecutive readings, however, will often duplicate to within a few tenths of 1%.
- (b) Exposure of the rectifier instrument to high temperatures, such as 50°C. , or to chemical vapors, such as sulphur fumes, may shorten the life of the rectifier.
- (c) The circuit of the instrument itself should never be opened when the rectifier is connected to the line, since this may allow full-line voltage to be impressed on the rectifier plates, and may damage the rectifier.

Despite these considerations, rectifier instruments play a very useful part in present day measurements, because the

permanent magnet moving coil construction gives higher sensitivity, and a more uniform scale than it is possible to secure with moving iron or dynamometer types.

Clamp-Ammeters.—Another type of instrument which is frequently employed in conjunction with a rectifier is the clamp-ammeter. This, however, is not a precision instrument but is used for rough check-ups of current in conductors, motors or transformer leads. Principally the instrument consists of a current transformer of the inserted primary type and a rectifier connected as shown in fig. 54 to a permanent magnet moving coil type instrument. Here the conductor forms the transformer primary winding, which induces a current in the transformer secondary.

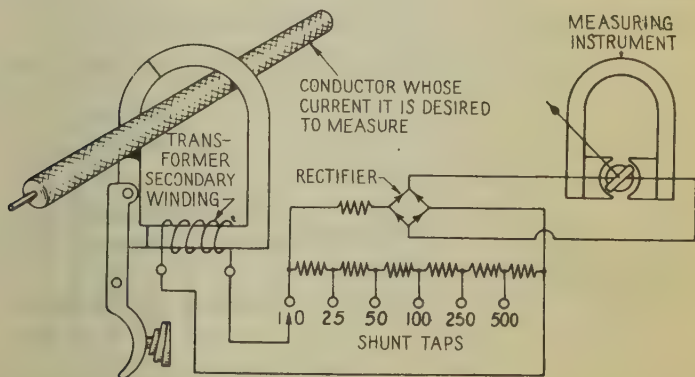


FIG. 54.—Typical arrangement of a clamp-ammeter circuit with rectifier instrument.

Various ranges are obtained by using an external multiplier arrangement. When connected as shown in fig. 54 a small proportional current is derived from the line current through

the use of the hinged core current transformer. This secondary current is then connected to a suitable tap on the multiple range rectifier type milli-ammeter to give the reading. The rectifier instrument is made into a multiple range device through the use of the multi-range series shunt.

In this combination it is possible to measure the current in any conductor by using the proper taps on the series shunt.

Thermocouple Type Instruments.—This instrument employs one or more thermo-junctions (thermocouples) which when heated directly or indirectly by an electric current, generates an electric current which when made to flow through a permanent magnet moving coil such as that shown in fig. 55 will make a deflection proportional to the difference in temperature of the junctions.

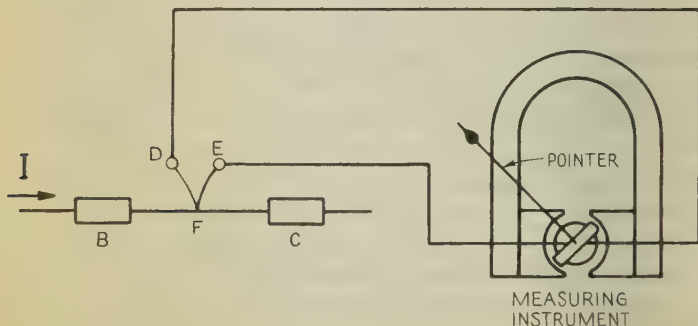


FIG. 55.—Basic type of heating element and permanent magnet moving coil mechanism for indication of direct, alternating and radio frequency currents. In the thermo-couple a potential is generated in the junction F , of the two dissimilar metals FE and FD , as the temperature of F , is increased over that of junction D and E by current flowing through the wire at BC . This potential causes a direct current to flow through the indicating mechanism, which is a function of the heating current in BC .

Because of the fact that the function of this instrument is based upon the temperature action of the current, the instrument is used industrially for measuring of temperatures as well.

When an alternating current is sent through the resistance wire which forms the heater, it will elevate the temperature of the junction in the same manner as before. Since the resistance of the heater remains substantially constant, the instrument scale can be marked in terms of the current flowing in the heater circuit.

As the temperature attained by the heater is proportional to the square of the current (I^2) flowing through it, the instrument scale will open up greatly as the current increases.

The voltage from a thermocouple is proportional to the difference in temperature between the heated junction and

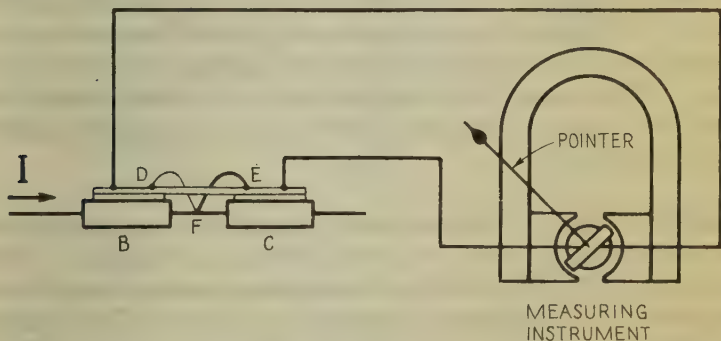


FIG. 56.—Showing arrangement used for cold-junction compensation in thermocouple instrument. Here the compensating heating element produces a thermo-electric voltage in the couple $D E$, which is a function of the current which flows in the circuit $B C$, and causes a temperature rise at point F . Since the couple voltage developed is a function of the temperature difference of its hot and cold ends, this temperature difference must be caused only by the current being measured. For accurate measurement then, points D and E must be at the mean temperature of point B and C . This is accomplished by attaching the couple ends D and E , to the center of separate copper strips whose ends are thermally in contact with B and C , but which are electrically insulated from them.

the point at which the thermocouple wires are connected to the copper leads of the instrument. Therefore, any change in the temperature of this latter connection point would result in an error in instrument indication.

To avoid errors caused by this condition, it is common practice to terminate the heater in rather massive blocks, and then bring the point at which the thermocouple leads join the copper circuit into good thermal contact with these blocks. This is usually done by connecting the leads to a thin copper plate, and separating them from the block by a thin mica strip. This is called cold-junction compensation (see fig. 56) and serves to maintain the connection at a fixed relation to the temperature of the heater.

The milli-voltmeters, used with thermocouples to measure current, must necessarily be more sensitive than those used with shunts, because the *e.m.f.* developed by a thermocouple is quite small. For example, such a thermocouple may have an output voltage of only 15 milli-volts, and an internal resistance of 5 ohms. This means that thermocouple instruments should be carefully handled, since the construction is necessarily somewhat delicate.

Hot Wire Type.—This instrument depends for its operation on the expansion by heat of a wire carrying a current. With reference to fig. 57, showing the principal parts of a hot wire ammeter, the instrument functions as follows: The current being measured, causes a wire through which the current flows to heat up and thus expand or increase in length approximately in proportion to the square of the current flowing (I^2). The change in the length or sag of the wire is amplified and arranged to drive the pointer.

Instruments of this type are made in different forms with various arrangements of their wires and parts. All of them, however, work upon the same principle. Due to the fact that this instrument functions as the result of the heating effect of the current, it can be used for measurements on both *direct current* and *alternating current* circuits.

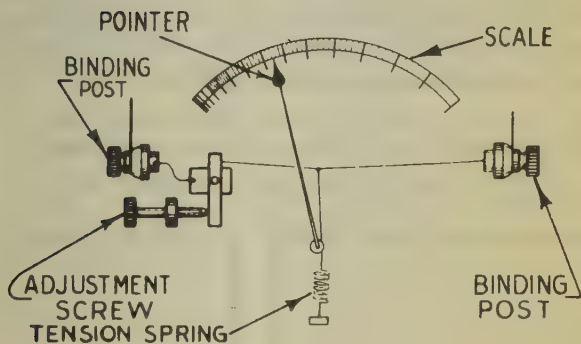


FIG. 57.—Showing principal arrangement of a hot wire type ammeter.

This instrument is not employed where great accuracy is desired. This is mainly due to instability due to wire stretch and lack of ambient temperature compensation. It is now being largely replaced by the more sensitive, more accurate and better compensated, permanent-magnet moving-coil combinations previously described.

Connections of Meters and Instruments

Measurement of Alternating Current.—The current in an electric circuit is measured by the ammeter. Always connect an ammeter in series with the load whose current it is desired to measure—*never across it*. Always ground the current transformer secondary.

If an ammeter is to be used on circuits of devices such as motors, that have a high starting current, short out the ammeter until after the starting period. Or, if the instrument is to be left in the circuit for some time, use a short-circuiting switch to avoid damaging the instrument. The switch can be opened at any time when a reading is to be taken.

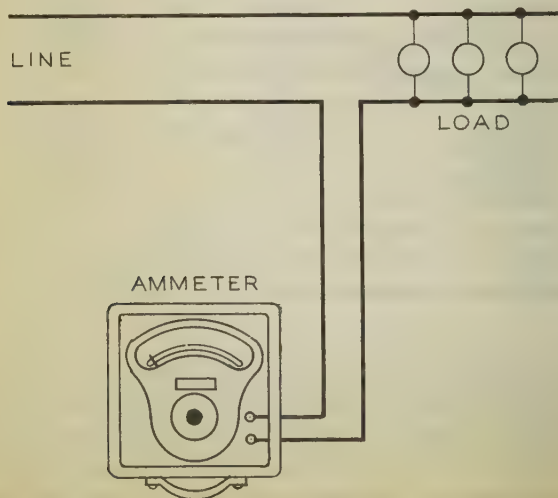


FIG. 58.—A.C. ammeter connection.

Measurement of Direct Currents.—If one side of the line is grounded, ammeters should be connected to that side. External and internal shunts are used by measurements of large current values. If the instrument reads backward, reverse the instrument leads. Various A.C. and D.C. ammeter connections are shown in figs. 58 to 62.

Measurement of Alternating Current Voltages.—The potential or voltage across a circuit is measured by the voltmeter. Always connect a voltmeter across the load whose voltage it is desired to measure—*never in series*. To extend the range of a voltmeter, multiplier may be used. If a higher rated voltmeter is not available, use a potential transformer. Always ground the potential transformer secondary.

Typical voltmeter connections are shown in figs. 63 to 66.

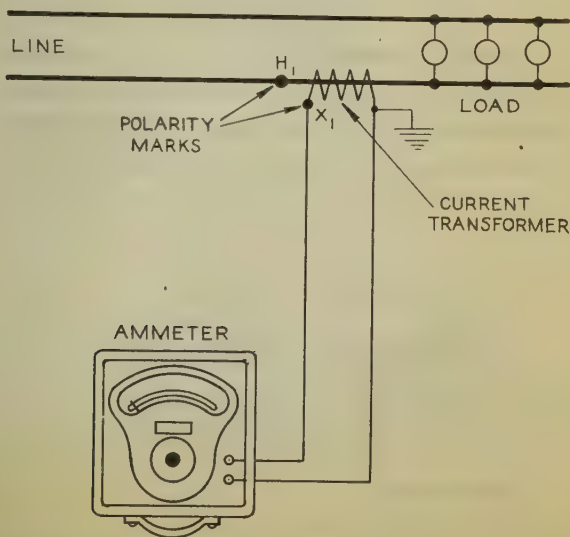


FIG. 59.—Connections of A.C. ammeter when current transformer is being used.

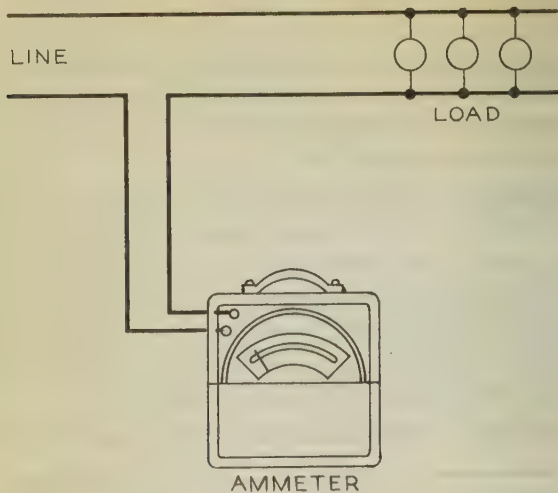


FIG. 60.—Connections of D.C. ammeter.

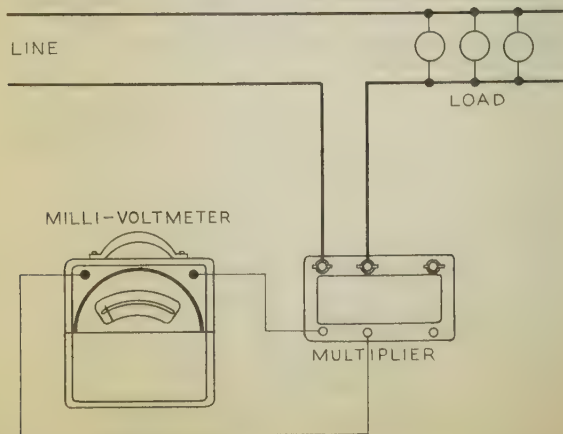


FIG. 61.—Connections when milli-voltmeter is used with shunt for measurement of direct current.

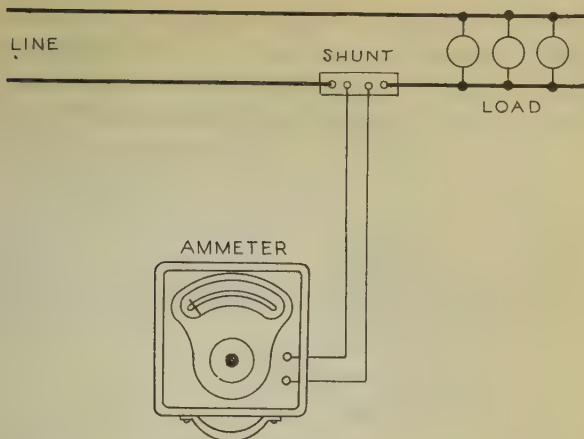


FIG. 62.—D.C. ammeter connection.

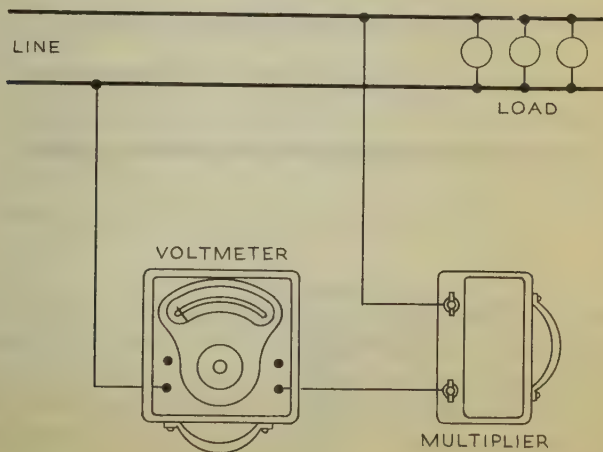


FIG. 63.—Connections of A.C. voltmeter when used with resistance multiplier.

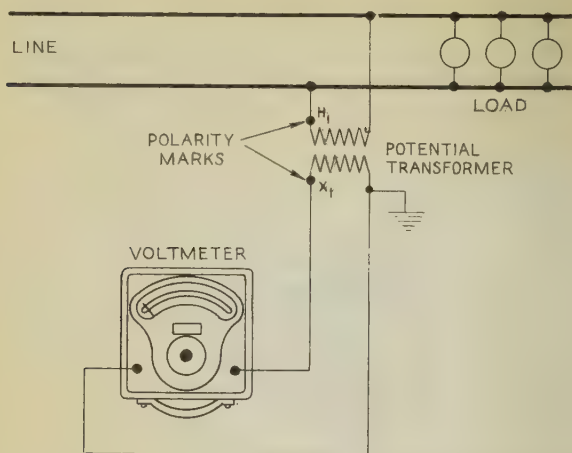


FIG. 64.—Connections of voltmeter when potential transformer is being used.

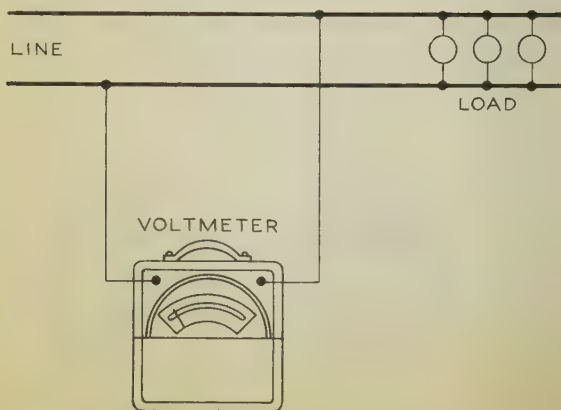


FIG. 65.—Connections of D.C. voltmeter.

Measurement of Direct Current Voltages.—If the instrument reads backward, reverse the instrument leads. Voltmeters are commonly equipped with an internal or external resistance (sometimes called multiplier) to extend the range of the instrument.

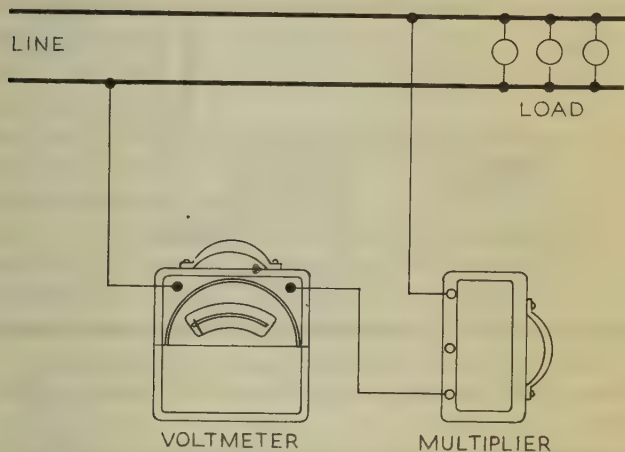


FIG. 66.—Connections of D.C. voltmeter when used with resistance multiplier.

Measurement of A.C. Power (Voltmeter and Ammeter Method).—The power in an electric circuit carrying a non-inductive load may be measured by the combined use of both instruments or by means of a wattmeter. An illustration showing the connections of the voltmeter and ammeter for power measurements is shown in figs. 67 and 68. In fig. 67, the voltmeter measures *line voltage*, not load voltage. The ammeter measures load current only.

In fig. 68, the voltmeter measures *load voltage*, not line voltage. The ammeter measures load current, plus voltmeter current.

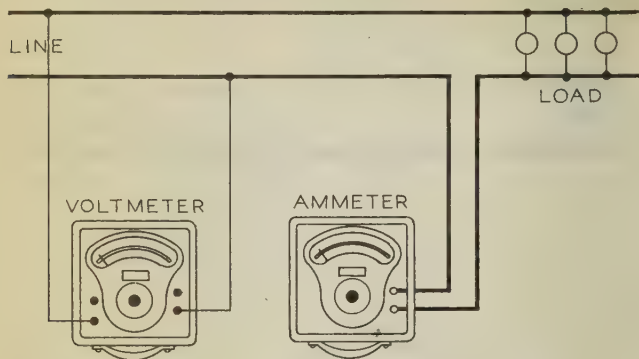


FIG. 67.—Voltmeter and ammeter connections with the voltmeter reading line voltage only.

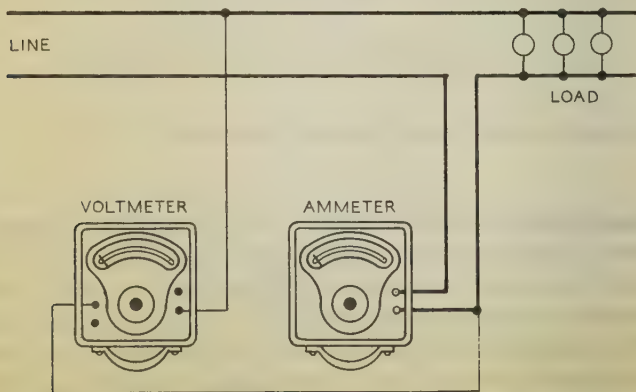


FIG. 68.—Voltmeter and ammeter connections with the voltmeter reading load voltage only.

Measurement of A.C. Single Phase Power (Wattmeter Method).—Methods of connections when power in a single phase system is measured by a wattmeter is shown in figs. 69 to 76.

In fig. 69, the instrument is measuring power load plus the loss in its own current coil circuit. If the instrument reads backwards, reverse the current leads.

Special precautions should be taken not to overload wattmeters. Potential transformers are usually employed on circuits above 300 volts.

On circuits of 750 volts and above potential and current transformers are generally used. Always ground the secondary of the potential transformer circuit.

Figs. 73 and 74 illustrate the connections when it is desired to measure the voltage and power consumption of the load simultaneously. In fig. 73, the wattmeter measures power load plus losses in the voltmeter and wattmeter potential circuits.

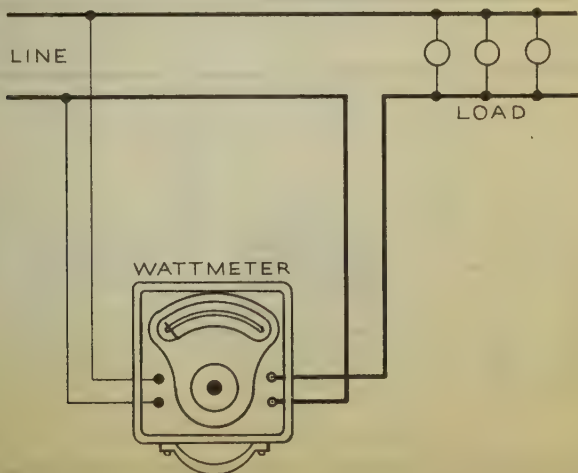


FIG. 69.—Wattmeter connections in a single phase circuit, with the instrument connected to measure the power load plus losses in its own current coil circuit.

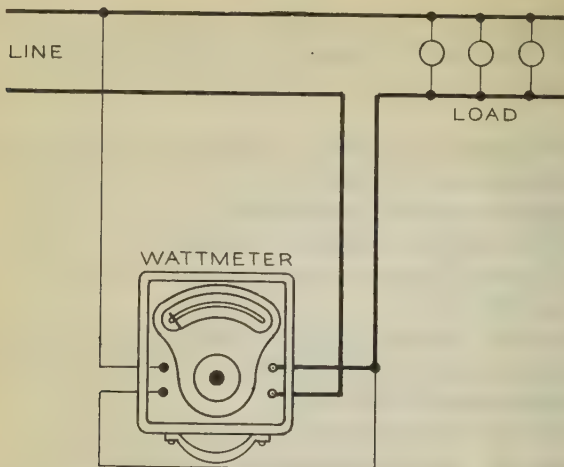


FIG. 70.—Wattmeter connections in a single phase circuit with the instrument connected to measure the power load plus loss in its own potential coil circuit.

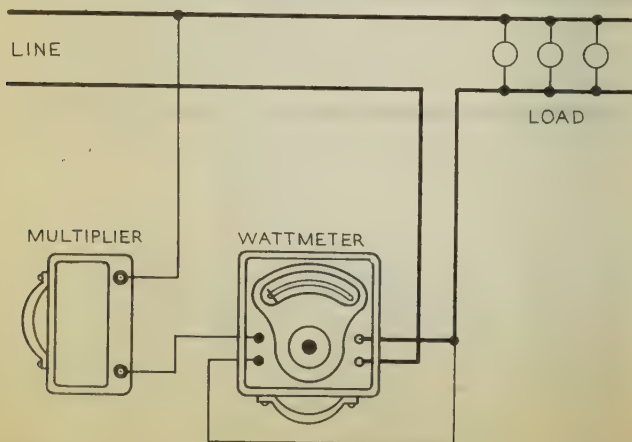


FIG. 71.—Showing wattmeter connections in a single phase circuit when resistance multiplier is used for the instrument potential circuit. Here the instrument is connected to measure the power load plus the loss in its own potential coil circuit and in the resistance multiplier.

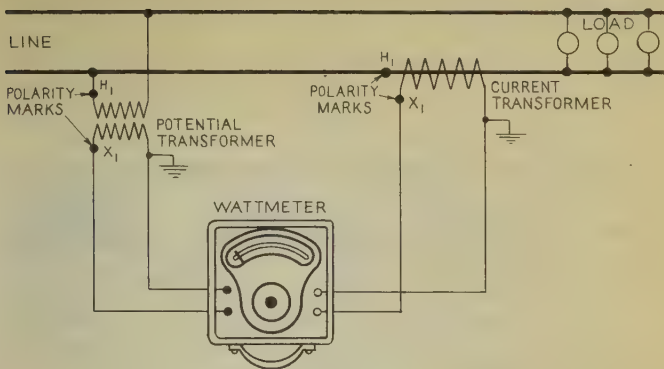


FIG. 72.—Connections of wattmeter in a single phase circuit, with current and potential transformer.

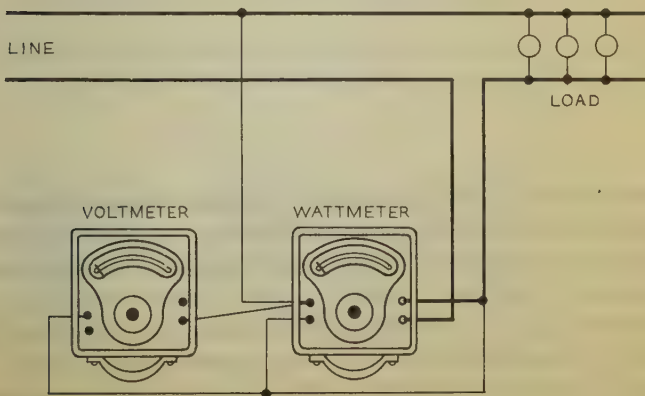


FIG. 73.—Connections of wattmeter and voltmeter in a single phase circuit.

In fig. 74, the wattmeter measures power load plus losses in its own current coil circuit.

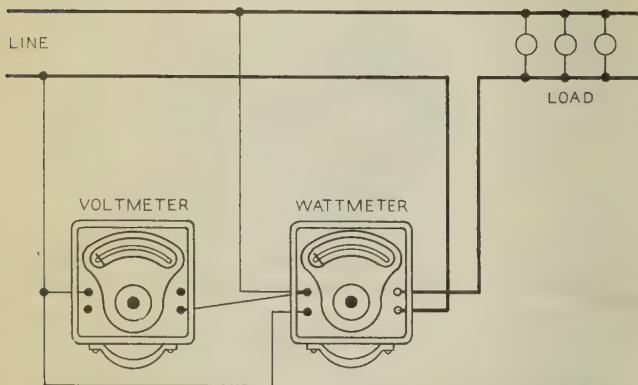


FIG. 74.—Optional connections of watt and voltmeter in a single phase circuit.

Measurement of Power Factor (Indirect Measurement).—

The power factor of a single phase load may be determined by dividing the wattmeter reading by the product of the voltmeter and ammeter readings. When the instruments are connected as shown in fig. 75, the wattmeter measures power load plus losses in the ammeter and wattmeter current-coil circuits.

In fig. 76, the wattmeter measures the sum of the power losses of the load, the potential circuit of the wattmeter, and the voltmeter.

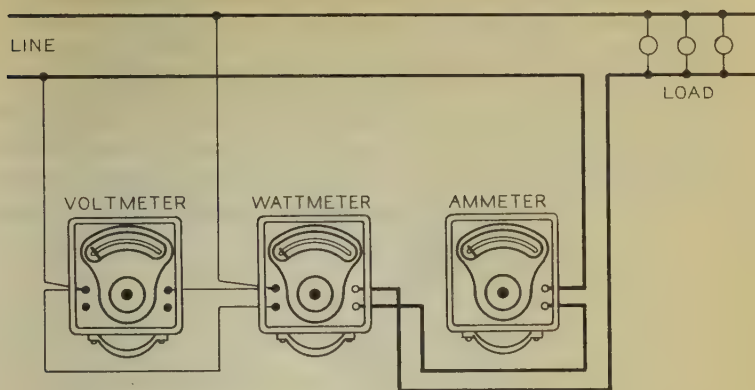


FIG. 75.—Connections of voltmeter, ammeter and wattmeter to a single phase load.

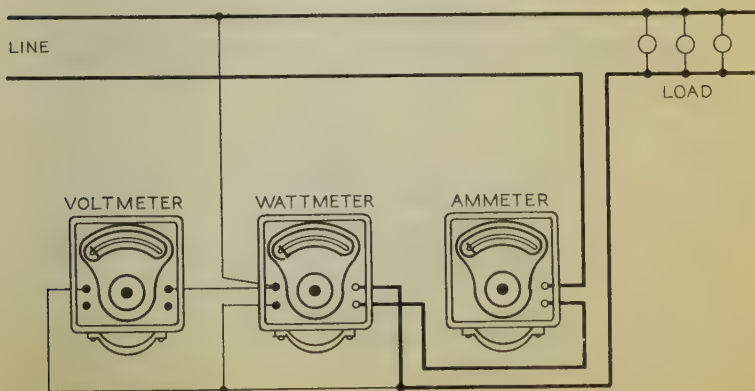


FIG. 76.—Optional connections of a voltmeter, ammeter and wattmeter to a single phase load.

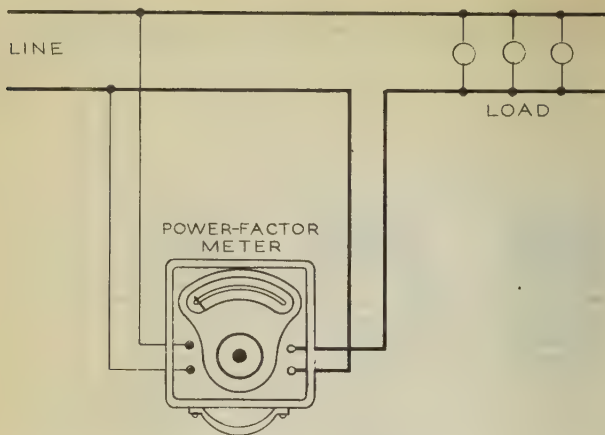


FIG. 77.—Connections of a single phase power factor meter.

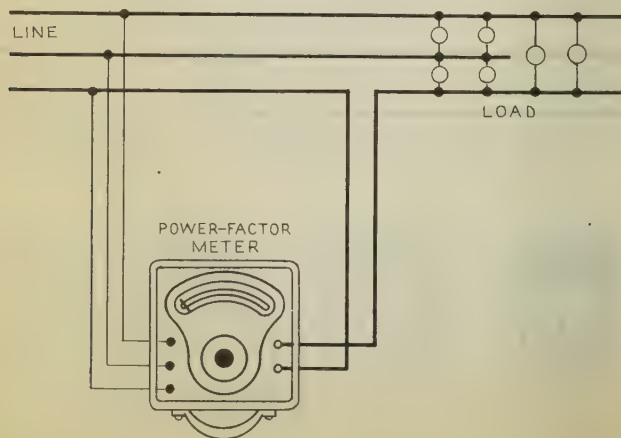


FIG. 78.—Connections of a 3 wire, 3 phase power factor meter.

Measurements of Power Factor (Direct Measurement).—

A more convenient method for direct readings of the power factor in single and polyphase circuits is by means of power factor meters connected as shown in figs. 77 to 79. These connections when made as shown are correct at all power factors. Polyphase power factor meters are intended for use in balanced circuits only. Single phase power factor meters should be used only at the calibrated frequency.

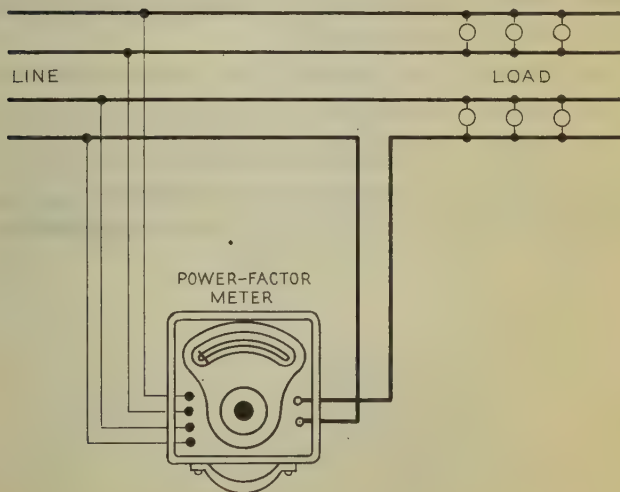


FIG. 79.—Connections of a 4 wire, 2 phase power factor meter.

Measurements of A.C. Polyphase Power.—Illustrations showing connections for power measurements in A.C. polyphase systems are shown in figs. 80 to 84. While only wattmeter connections are shown, the ammeter and voltmeter can be connected as shown in figs. 75 and 76.

In fig. 80, the power of the system is three times the indications of the wattmeter. The wattmeter indicates its own potential losses plus the power in one phase of the load. In fig. 81, the two wattmeters will not indicate alike except at unity power factor. Above 50% power factor, the three phase power is the sum of the two readings. Below 50% power factor, it is necessary to reverse the reading of one wattmeter (by reversing its current leads) and then take the difference between the readings of the two instruments.

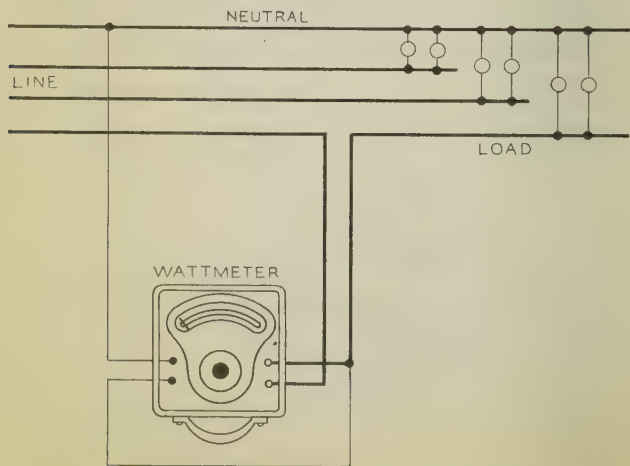


FIG. 80.—Connections of a single phase wattmeter in a balanced 3 phase, 4 wire circuit.

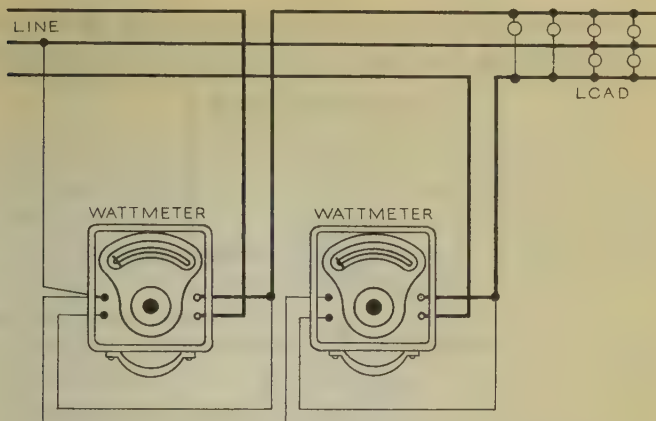


FIG. 81.—Connections of two wattmeters for 3 phase balanced or unbalanced voltages or load.

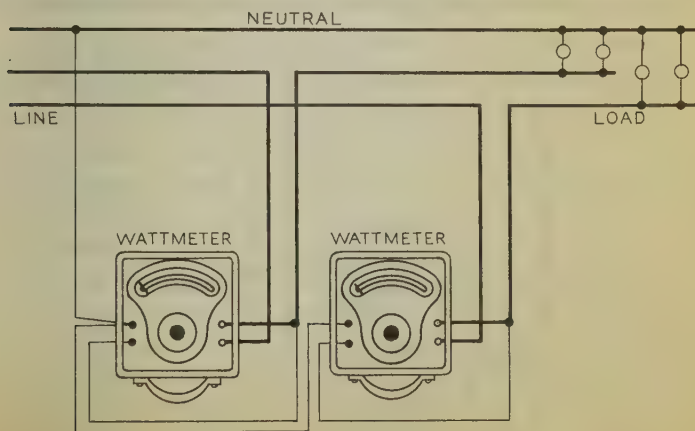


FIG. 82.—Connections of two wattmeters for 2 phase, 3 wire balanced or unbalanced load.

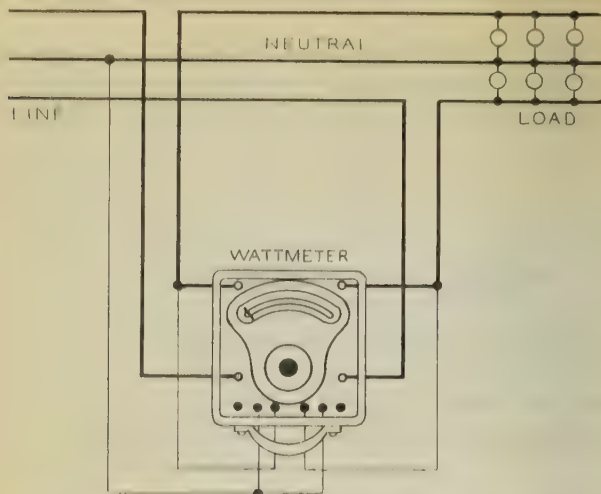


FIG. 83. — Connections of a polyphase wattmeter in a 2 phase, 3 wire circuit, balanced or unbalanced voltage or load.

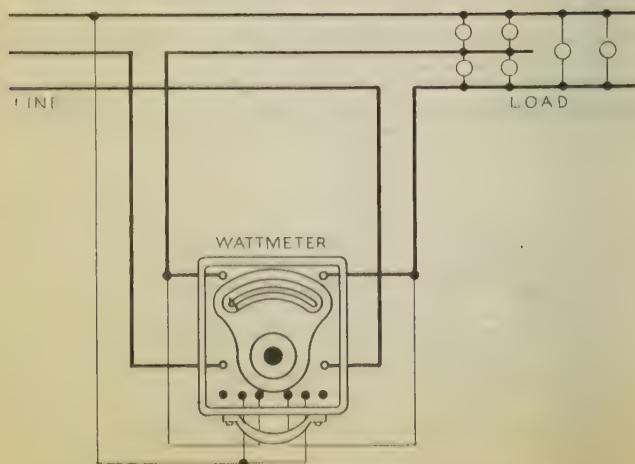


FIG. 84. — Connections of a polyphase wattmeter in a 3 phase, 3 wire circuit.

Maintenance Pointers on Electric Instruments

Selection of Instruments.—Electric measuring instruments will give good service if accorded the care which mechanisms of their delicacy deserve. If mistreated, they may fail to function properly and considerable loss in both time and money will result. It is, therefore, of the greatest importance that thoughtful attention be given to their care and use.

Best results in the use of instruments depend upon the proper original selection.

The accuracy desired and the cost are the two important factors in selection. Instruments should be chosen to give the required accuracy at the least cost.

The following guide for proper selection of instruments are recommended by the *General Electric Company's engineers*:

1. What accuracy is desired?
2. Should it be A.C. or D.C.?
3. Should it be portable or for switchboard mounting?
4. Should it be indicating or recording?
5. What is the desired rating? The range should be such that the instrument reading is usually above one-third scale.
6. If a switchboard instrument is desired, should it be of the surface mounting or semi-flush mounting type?
7. Can a standard instrument listed in the manufacturer's catalog be utilized in order to obtain lowest cost and best delivery?
8. What effect will the instrument have on the circuit in which it is to be used? For example, some applications require a voltmeter with high resistance for minimum

current drain. Or, an ammeter may have to have a low volt ampere rating if it is to be used with a through type current transformer.

9. Conditions under which the instrument is to be used are important. Indoor or outdoor, humidity or corrosive atmosphere may require special instruments.

Setting Up Instruments for Use.—When any questions arise as to the use of a specific instrument, it is recommended that the information be obtained from the manufacturer.

The following pointers should be observed before placing *any instrument* in service:

1. Manufacturer's instruction book accompanying the instrument should be read carefully.
2. Instrument should be handled carefully to avoid all vibration or shocks which may injure the instrument bearings.
3. From the name plate of the apparatus on which the measurement is to be made, estimate the value of the current, voltage, etc., to be measured.
4. If an instrument has more than one tap or range, make connection to the highest range first to avoid injury to the instrument.
5. Instruments should always be read when in their normal operating position; that is, portables should be in a level, horizontal position. Switchboard types in a vertical position.

The following pointers should be observed before placing *any portable instrument* in service:

1. Metal benches should be avoided, as the instrument indication may be affected by the proximity of the metal.

2. Proper sized leads should be used. Terminals should be clean to avoid high contact resistances, particularly in the case of milli-voltmeters used with shunts. Lead wires should extend away from the observer to avoid accidentally pulling the instrument off the table.
3. Whenever a shunt is used with a milli-voltmeter to read current, always check to make sure the leads with which the instrument was calibrated are being used.
4. If external resistance multipliers are used, check both the serial number of the instrument and that of the multiplier to make sure of the correct combination.
5. The instrument zero setting should be checked. If the pointer is slightly off zero, reset to zero by adjusting the external zero shifter. Never try to compensate for a bent pointer by moving the zero shifter.
6. The instrument should not be used in strong fields such as near cables or bus bars. Presence of a magnetic field which is affecting the reading of an instrument can be detected by turning the instrument (clockwise or counter-clockwise) 90° at a time, and taking a reading in each position. If a difference is noted in the readings, some stray field is present.
7. Unshielded instruments should not be placed close together, as the reading of one instrument may be affected by the magnetic field of the other.
8. When an ammeter or shunt is to be connected into a circuit, always connect it into the grounded side, if possible.
9. When a voltmeter is to be connected to a circuit, always connect the leads to the instrument *first*. This avoids loose leads which may be hot. Be sure that voltmeter leads are properly insulated for the voltage to be checked.

10. Instruments, shunts and leads should always be arranged in such a way that there is no danger of knocking them off the table or tripping over the leads; and if any high voltages are to be measured, the arrangement should be such that no one might accidentally touch the high voltage equipment.
11. Whenever an instrument is to be connected to a current transformer secondary, always short circuit the transformer secondary terminal before the primary is connected in the circuit to avoid dangerously high voltages. *The current transformer secondary must be grounded.*
12. When a potential transformer is to be used, always make sure that the instrument is connected to the secondary or low voltage side. *The potential transformer secondary circuit must be grounded.*

The following applies to switchboard instruments:

1. Switchboard instrument should be mounted on panels in accordance with the manufacturers' instructions.
2. Never mount a switchboard instrument on a panel until all other work on the panel is completed, as any pounding or vibration may affect the instrument.
3. The general precautions given under Portable Instruments also apply to switchboard instruments.

Precautions in the Use of Instruments.—The following pointers should be observed in the use of any electric instrument:

1. Always try to have the instrument reading between $\frac{1}{2}$ and $\frac{3}{4}$ full scale. Never read below $\frac{1}{3}$ full scale if it can be avoided. (See paragraph 11.)
2. Never touch bare terminals or binding posts while an instrument is energized.

3. The instrument reading should be made from directly above the scale to avoid errors.
4. If a split core current transformer is used with an ammeter, always make sure that the transformer core joint is free from dirt which may introduce a considerable error in the reading.
5. To avoid temperature errors, instruments should never be used in extreme temperatures. Special temperature compensated instruments are used for these conditions.
6. Special instruments should be used to measure motor starting currents or welding currents.
7. Clean the glass of an instrument by using a damp cloth. A dry cloth may induce a static charge on the glass and affect the instrument reading. If the instrument glass does become charged, it can be dispelled by breathing on the glass.
8. Never slam the cover of an instrument. Be sure the nuts of the binding post are tight, even when the instrument is not in use.
9. If an instrument is overloaded or dropped, or if for any reason the accuracy is doubted, the instrument should be checked against another instrument on several points before it is used again.
10. Tapping an instrument with the fingers will remove any slight stickiness. If the pointer movement is erratic, and if tapping causes appreciable movement of the pointer, the instrument bearings may require attention and should be examined by a competent instrument-repair laboratory.
11. Instrument accuracy is always expressed in terms of the percentage of error at the full scale point, so maximum accuracy is obtainable by keeping the reading as high

on the scale as possible. This calls for the selection of a properly rated instrument. The accuracy of the readings is determined as follows: Assume that there are 100 scale divisions and that the accuracy is 1% of full scale. A scale reading of 100 means that the quantity measured contains 100 units plus or minus 1%, or plus or minus 1 scale division; that is, the correct value lies between 99 and 101 units. However, while a scale reading of 20 ($\frac{1}{5}$ of full scale) also has a margin of error of plus or minus 1 division, the error there is 5 times as great, or plus or minus 5%.

12. Watt meters should be so connected into a circuit that the current coil and the potential coil are at the same potential. (The potential terminal, which is connected in the same side of the line with the current coil, is usually identified by the zero or + marking.)
13. This is particularly important where multipliers are to be used, as it is possible to obtain a potential difference between the current and potential coils high enough to cause a breakdown.
14. Instruments with single ratings are preferable because if, by accident, the single rated instrument becomes defective, the use of only one instrument is lost; whereas if one tap of a multi-rated instrument burns out, the entire instrument has to be repaired. For example, instead of having a voltmeter rated 600/300/150/75 volts, it would be preferable to have two instruments rated 600/300 and 150/75 or better still, to have four separate instruments.
15. Where rectifier instruments are used in A.C. circuits to measure A.C. values, the wave form should be known, as rectifier instruments are normally calibrated on sine-wave A.C. circuits.

Double-Duty Instruments.—Certain types of instruments can be used for measurements of both A.C. and D.C. currents and voltages. Thus, the dynamometer and the magnetic-vane instrument, previously described can be used on both A.C. or D.C. circuits.

With the iron-vane instrument used on D.C. circuits, reverse readings should be taken, the average value being the correct value. A D.C. instrument of the permanent magnet moving coil type, however, cannot be used on A.C. circuits.

A polyphase wattmeter can be used to measure the power in a single phase circuit (within the current and voltage range of the instrument) by connecting the two current coils in series and the two potential coils in parallel. With the wattmeter so connected, the scale readings should be divided by two, to obtain the true power value.

For determination of power factor of a single phase circuit, a wattmeter, voltmeter and ammeter may be used. Power factor is the wattmeter reading divided by the product of the voltmeter and ammeter readings.

For a balanced three-phase three-wire circuit, the power factor is determined by dividing the net wattmeter reading (the algebraic sum of the readings of two single phase wattmeters, or that of a polyphase wattmeter) by the product of the ammeter and voltmeter readings multiplied by 1.73.

Calibration of Instruments.—How often an instrument should be calibrated depends entirely on its use and the accuracy desired.

If calibration standards and equipment are not available, instruments of nearly the same rating can be checked against each other. If wide discrepancies are noted, the instrument which reads incorrect should be checked by a competent laboratory technician or returned to the manufacturer for correction.

If the meter or instrument requires a new bearing or jewel, it is advisable to replace the pivot as well, as the old one may have become injured especially if the meter has been operating with a damaged jewel.

When inserting a new jewel or when replacing a jewel after having removed the moving element, see that the top bearing clamping screw is loosened so that this bearing is free to move, thereby preventing the possibility of a damaged jewel or shaft. See that the top bearing is properly set and clamped after inserting and adjusting the lower bearing.

To replace the pivot, remove the jewel screw from the meter and insert the pivot wrench in place. Clamp the pivot in the end of the wrench and unscrew. Replace the pivot by a new one and screw it into the shaft. Apply a drop of fine watch oil to the jewel and insert the new jewel screw.

Whenever the registering element of a meter is oiled, it should be wiped carefully afterwards to remove any excess oil. Only the best quality of watch oil must be used for this purpose.

CHAPTER 13

Motor Testing

General.—The purpose of testing as applied to motors and generators is primarily to make sure that they have been properly constructed, that they meet the manufacturers' guarantee, and that they will perform their assigned duty with safety under normal conditions of operation.

Although the tests herein described deals principally with direct current machines, they may, with certain modifications be applied to alternating current machines as well.

The nature of the various tests and their functions are substantially as follows:

1. To ascertain that the machine complies with the specifications under which it was constructed.
2. To determine whether the machine is suitable for a given duty.
3. To determine the maximum capacity of the machine as limited by considerations of safety and liability to undue deterioration.
4. To determine the characteristics of the machine so that it may be known in advance how it will perform under given conditions.
5. To facilitate the location of trouble and to familiarize the operator with the characteristics of the machine.

Such tests as applied to commutating machines may be grouped and classified according to the nature of the test in the following manner:

1. Preliminary inspection and adjustment.
2. Resistance measurements.
3. Characteristics.
4. Efficiency.
5. Heating.
6. Miscellaneous tests.

Instruments.—Prior to making a test it is important that the necessary and correct instruments and accessories be available in addition to the proper source of power.

The instrument used depends upon the nature of the test to be made. Instruments and accessories most commonly used are: Tachometers, frequency indicators, meggers, megohm-meters, ohmmeters, voltmeter, ammeters, shunts, graphic recording instruments, wattmeters, temperature meters, potential transformers, current transformers, etc.

For construction, maintenance and methods of instrument connections, see Chapter 12.

Instruments Caution

1. Electrical instruments should not be used unless the date on the calibration card is not over two weeks old.
2. The zero position of an instrument in use should be checked at least twice a day.
3. No instruments should be used which are not suitable for the work.
4. No readings should be taken at scale points below which there is a black or colored band.
5. Instruments should always be tested for stray fields.

6. Any portable instruments having switches on them should not be left continually in circuit.
7. Voltmeters must not be left connected to inductive circuits.
8. A special switch provided for the purpose of disconnecting the voltmeter and table from the field of a synchronous motor when starting should always be used.
9. The voltmeter should be disconnected from the field of a synchronous converter before starting.
10. No field circuit should be opened while a voltmeter is connected across it.
11. Frequency meters should never be put in circuit until the voltage has been measured by a voltmeter, and no frequency meter or any other meter should be used on a circuit of higher voltage than the rated voltage of the instrument.
12. The residual voltage of a machine should never be used to operate a frequency meter.
13. Instruments should not be left lying around where they are unprotected or subject to injury.

Preliminary Adjustment

Wiring.—The power for testing is usually delivered through properly protected switchboards and all precautions should be observed with regard to safety to attendants, instruments and machinery associated with the work. This is particularly important when dealing with high voltage sources of power.

A wire misplaced during a test, a wrong switch thrown, or any other careless action may result in very serious consequences to attendants or to apparatus. Therefore, it is necessary to know the nature and wiring of a circuit before any switch or

instrument manipulation takes place. It is particularly important to see that all cables and terminals are properly insulated, especially those carrying injurious voltages.

Machine Inspection.—A careful inspection of the machine should be made prior to any test, and every point connected with the field, armature, commutator, brushes, brush rigging, terminal block, etc., should be noted to see that it conforms with the manufacturer's specifications.

In addition the general form of the field frame, the number of field coils, and poles (main and interpoles) and the method used to connect the terminals of the windings of one field coil to another should be noted. The number of terminals on each coil will indicate the form of field winding, that is, whether *series*, *shunt* or *compound*.

If it is a compound machine, it should be noted whether the two windings are separate or whether one is over the other, noting which one is on the outside. The method of ventilation, whether it involves open or enclosed frames and the use of fans should be observed.

Armature winding construction should be noted, whether it is *lap* or *wave* and it should be noted whether the conductors are wound directly on the armature core or imbedded in slots.

The commutator segments should be counted and the method of securing the armature winding to them noted, that is, whether they are clamped, screwed or soldered to the commutator segments.

The type and number of brushes should be noted, together with the mechanical features, and method of securing the rocker arm.

When preparing commutating machines for test, the brushes must be equally spaced around the commutator, 180 electrical degrees apart. The brushes on the stud must align properly

with each other, and with commutator bars, from the front to the back end of the commutator. To space the brushes, place a strip of paper tape around the commutator and mark the paper where the ends overlap. Remove the paper tape and divide it with a scale or dividers into as many equal divisions as there are poles on the machine. Then replace the paper around the commutator and place the overlapping ends together. Space the brushes by the marks on the paper, taking care that the holders are clamped to the stud in the proper position.

In some cases brushes are run trailing and in other cases leading, with reference to the direction of rotation. Radial brushes are also sometimes used.

When the brushes have been set, fit them to the commutator surface, using a strip of sandpaper between the commutator and the brush surface. Coarse sandpaper should be used first to obtain an approximate fit, followed with very fine sandpaper for a finish.



FIGS. 1 to 3.—Showing leading, trailing and radial brushes, respectively.

A close and accurate fit on the commutator is essential to obtain good commutation results. When sandpapering, the sandpaper must be held close to the commutator to prevent rounding the tip of the brush when drawing the paper away.

Sometimes the best results can be obtained by drawing the sandpaper in the direction of rotation, while other times the best results can be obtained by drawing the sandpaper in the opposite direction to rotation.

When the sandpapering of the brushes is finished, the resulting carbon dust must be blown from the armature, or rotating part. The air blast should be directed away from the rotating part so that the carbon dust is carried completely away and cannot sift into the winding. Leading, trailing and radial brush setting is shown in figs. 1 to 3.

The following are some of the more common defects which may appear in motors and generators:

1. Copper bridges formed between the bars over the side mica of the commutator due to improper turning.
2. Bent end conductors of commutator leads.
3. Improper brush staggering.
4. Improper alignment of brushes with commutator bars.
5. Damaged insulation of armature and field coils.
6. Broken insulation boards on fields.
7. Insufficient clearance between bare electrical terminals or conductors and ground.
8. Poor joints between electrical conductors.
9. Loose terminals, bus rings, or other connections improperly supported.
10. Brush pigtails too long or touching the armature risers.
11. Insufficient clearance between a brush stud or various parts of fittings and ground.
12. Incorrect brush spring pressure and defective spacing of collector ring taps.

The manufacturer's name plate furnishes additional information as to the rating of the machine, terminal voltage, current

at full load, type of winding, revolutions per minute of the armature, etc.

Lubrication.—All machine bearings should be provided with oil wells of sufficient capacity. When oil ring lubrication is used, the lubricating oil must not be allowed to reach a level so low in the oil well that the ring does not dip into it. For high bearing pressures, or high speed, some form of forced lubrication is used. The oil is forced into the bearing, either on the bottom or the lower quarter, and enters the bearing at a point such that the revolving shaft draws the oil under the shaft.

Oil from forced lubricated bearings is usually returned to an external cooling tank, where its temperature is reduced before it is pumped back into the bearing. Oil rings and forced lubrication are occasionally used on the same bearings, so that if the oil pressure fails, the rings will supply enough oil to prevent danger until the oil pressure can be restored.

A properly designed bearing may run hot from the following causes: oil ring sticking, scarcity or poor quality of lubricating oil, excessive local pressure in the bearings, insufficient relief on the sides of the bearing, improper alignment and excessive belt pull, or current flowing from the shaft to the frame.

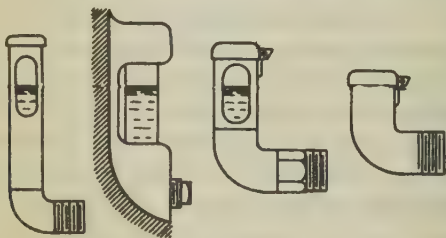
The remedy for the greater part of these troubles is obvious. In the case of excessive local pressure in the bearing, or insufficient relief on the sides, the remedy is to remove the high spots of the babbitt or bearing metal with a scraper, and increase the side clearance.

Before starting a machine, all bearings must be filled with the proper amount of oil. Bearings which contain gauge glasses should be filled until the glass is about two-thirds full. Bearings containing an overflow cup gauge should be filled until the oil is about $\frac{1}{2}$ inch from the top of the gauge. Bearings should be carefully filled, and no oil should be spilled on the housing or

shell, or upon other parts associated with the bearing, because a false impression may be obtained as to oil leakage or throwing when under test.

To give the bearing a critical test for oil leaking or throwing, the dividing line between the cap and bearing pedestal and between bearing brackets, should be painted with whiting. The end of the commutator or field spider adjacent to the bearing should also be given a white coating, so that it is possible, after a comparatively short run, to detect the slightest leakage or throwing of oil.

Bearings with the end of the shell visible should be filled with oil until it touches the lower part of the shell at the end of the bearing housing. Overflow gauges, figs. 4 to 7, used on small machines, should be filled to within $\frac{1}{16}$ of an inch of the overflow. In filling the bearings, a funnel must be used and the oil inserted into the sight holes for the oil rings, or through the opening above the shaft at the end of the bearing housing.



FIGS. 4 TO 7.—Various types of oil gauges.

During test, no oil should be allowed to leak or be thrown from the bearings upon the rotating parts or windings. This is especially true with reference to commutating machines, where it is important that lubricating oil be kept away from the

commutator, brushes and fittings. Should oil leaking or throwing on these parts be detected during the test, the test should immediately be discontinued and the cause of leakage removed. If bearings under test rise 40° Centigrade above the room temperature, the fact should be referred to the engineer in charge of the test, for no properly designed bearing should rise above 40° under normal conditions.

The various resistance test made on commutating machines may be classified as follows:

Resistance Measurements

1. Armature resistance tests.
2. Tests for location of defects.
3. Field winding resistance tests.
4. Insulation resistance tests.
5. Dielectric strength tests.

Armature Resistance.—Armature resistance includes not only the resistance of the armature itself, but also the resistance of the brushes and brush contacts, that is, the total resistance of the armature circuit from terminal to terminal.

It is nearly always measured by passing a known current through the stationary armature and measuring the voltage drop between the brushes and also across the terminals of the machine.

Noting the current flow and the voltage drop it is a simple matter to calculate the resistance of the various parts of the circuit.

In this connection it should be observed that the brush contact resistance is not constant, but is varying approximately in inverse proportion to the current, from which it follows that the voltage drop of any brush is approximately constant regardless

of the load. The brush contact drop is approximately one volt for carbon, 0.75 volt for graphite and 0.10 volt or less for copper brushes.

Since any resistance will vary with the temperature, that is, the resistance of the armature increases with the temperature, the value obtained with the armature cold will be considerably lower than that obtained with the armature hot. Thus, the resistance value obtained during the test will be only approximately correct.

A simplified method of obtaining armature resistance is to pass a current through the armature and also through a standard resistance of approximately the same value and current carrying capacity, and comparing the drop of potential across each in which case the current need not be measured.

Test for Locating Defects.—Direct and alternating current windings may be tested for grounds, short circuits, and high resistance joints; also wrong connections, wrong polarity, etc.

If a low resistance ground in armatures with commutators has been developed, it may quickly and accurately be located by the following method: a low-voltage current, which is sufficient to give a readable deflection on a galvanometer or millivoltmeter, is passed through the armature windings from one commutator bar to the next, as shown in fig. 8. A line is connected from the galvanometer to the ground, and the other galvanometer connection is placed on one of the commutator bars. The supply and galvanometer leads are then passed from segment to segment. When a full deflection is obtained, the coil is grounded.

Measuring the ohmic resistance of the winding will sometimes reveal a wrong connection, which, on a bar-to-bar measurement, would give a uniform deflection all around the commutator. Series or wave windings may sometimes have all conduc-

tors joined in series, but in the wrong order, making the armature inoperative. In case of multiple or lap windings, double, triple, or even quadruple-spiral re-entrant windings are possible, whereas a single spiral is required. In taking a resistance measurement of the armature, see that the measurement is made from the proper commutator segments.

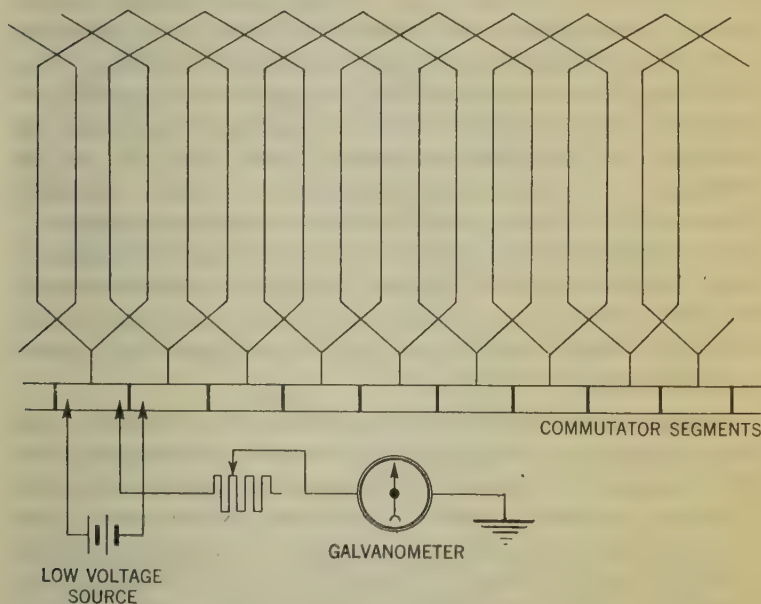


FIG. 8.—Showing method of testing D.C. armature winding for defects.

Special clips are attached to the commutator bars, and spaced the number of bars apart equal to the total number of bars divided by the number of poles. Each alternate clip is connected in parallel to one terminal of a double bridge, and the remaining clips are connected in parallel and to the other termi-

nal of the double bridge. The resistance reading then obtained is the true running resistance.

Alternating-current windings are similarly tested for grounds, short circuits, open circuits, wrong connections, polarity, etc. In testing for grounds, the methods and apparatus used are similar to those used for direct-current machines, except that with alternating current, the voltage generated is usually higher. Consequently, the testing voltages are correspondingly higher, and greater care must be taken in testing. Place the testing equipment as near to the apparatus as possible, as the additional capacitance of the testing lines may raise the voltage at the receiving end much higher than that at the operating end. Unless this precaution is taken, excessive voltage may be applied, and this may damage the insulation.

If a ground develops, a resistance measurement will generally locate the point at which it occurs, unless each phase has two or more multiple circuits. In this case, it may be more readily located by opening one or more of the end-connection joints, and separating the circuits.

A measurement may be taken as shown in fig. 9, which represents a single circuit or phase of an alternating current machine, with the ground as shown. If the resistance between *A* and *B* is one ohm, between *A* and *G*, is 0.35 ohm, and between *B* and *G*, is 0.65 ohm, the location of the ground is 0.35 of the distance between *A* and *B*, from *A*. Since ten coils are in the circuit, the measurements show that the fourth coil is grounded, counting from *A*.

In the case of an alternating current winding, the ohmic resistance measurement will not always detect a wrong connection, such as a reversed coil, pole section, or phase; for, although the copper resistance would be measured correctly, the total winding might be partly reversed, and therefore,

inoperative. Such faults can be discovered by a polarity or impedance test with alternating current. For this purpose, a single phase current can be used, since a reading may be taken on the different circuits or between pairs of terminals successively, by shifting the testing lines until all windings have been tested.

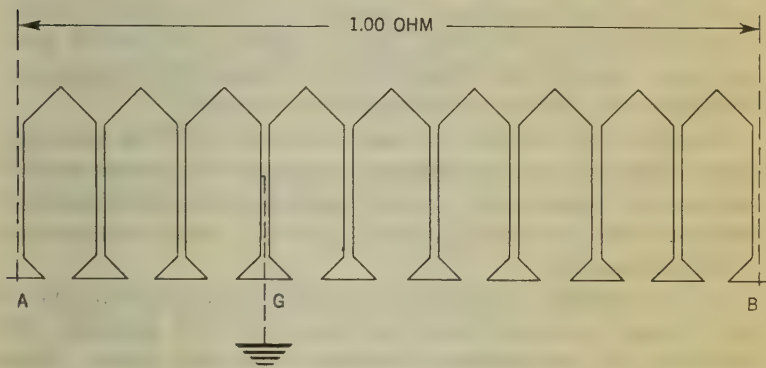


FIG. 9.—Method of testing A.C. winding for ground.

Series Winding Resistance.—Since this resistance is of a very low value, special galvanometer measuring sets are generally used. A considerable percentage of the resistance of a series field may consist of contact resistance between the spools.

Shunt Winding Resistance.—This resistance is generally determined by passing a known current through the coils and measuring the drop of potential across the field terminals.

With a given current flowing through the field, the voltage drop on any one coil of a direct current machine should never be more than 5% higher or lower than the average drop.

Insulation Resistance.—This test gives an indication of the condition of the insulation of the machine. The actual value of the resistance varies greatly in different apparatus depending on the type, the size, the voltage rating, etc. The principal worth of such measurements, therefore, is in the relative values of insulation resistance even slightly higher than for the good material. Surface dirt or moisture that causes loss of insulation resistance may also cause low dielectric strength.

Insulation resistances will vary inversely with the temperature. That is, the insulation resistance will decrease with increase in temperature. As an approximation the insulation resistance will be halved by an 8° to 10° C. rise in temperature of the apparatus.

As an example, when new insulation or insulation that is very damp, is being dried, the resistance will generally fall rapidly as the temperature is raised to a drying value. After falling to the minimum for a given temperature, the resistance will rise as moisture is expelled from the insulation.

Measurements of insulation resistance are most readily obtained with a megger or an ohmmeter. For general maintenance work the megger should be of the 500 volt rating, although for special tests a 1,000 volt or even 2,500 volt megger may be required.

When a 500 volt or 600 volt direct current circuit is available satisfactory results may be secured with a D.C. voltmeter having high internal resistance. The method of measurement is first to read the voltage of the line, then to connect the resistance to be measured in series with the voltmeter and take a second reading.

The measured resistance is then calculated by using the following formula:

$$R = \frac{r(V - v)}{v(1,000,000)}$$

In which

V = Voltage of the line.

v = Voltage reading with insulation in series with Voltmeter.

r = Resistance of voltmeter in ohms (generally marked on label inside the instrument cover).

R = Resistance of insulation in megohm (1,000,000 ohms).

The method of connecting the apparatus is shown in the diagram, fig. 10.

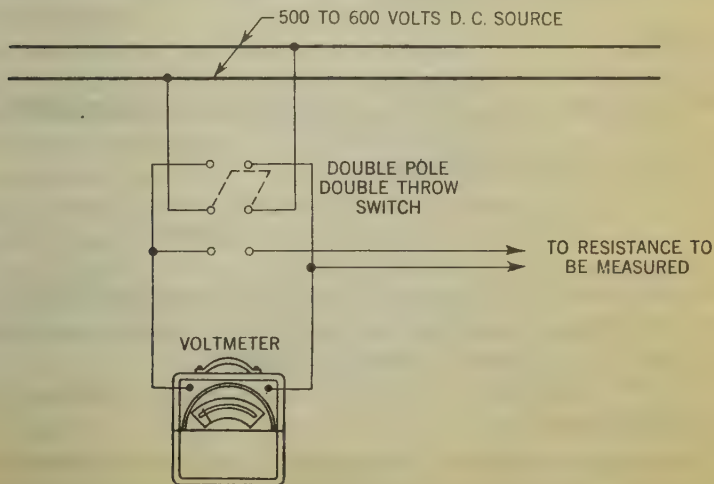


FIG. 10.—Showing connections for measuring insulation resistance.

If a grounded circuit is used in making this measurement, care must be taken to connect the grounded side of the line to the frame of the apparatus to be measured, and the voltmeter between the windings and the other side of the circuit.

Voltmeters having a resistance of one megohm are now made for taking insulation resistance measurements. If one of these instruments is used, the calculation is somewhat simplified since $r = 1$ and the foregoing formula becomes:

$$R = \frac{V}{v} - 1$$

As an example: In testing a generator insulated for 13,800 volt service with a line voltage V , of 600; using a voltmeter having an internal resistance r , of 1,000,000 ohms (one megohm); assume the voltage v , indication with the meter in series with the insulation to be 40:

Then:

$$\text{The resistance} = \frac{1,000,000(600 - 40)}{40 \times 1,000,000} \text{ or } R = 14 \text{ megohms.}$$

or as this is a megohm meter:

$$R = \frac{600}{40} - 1 \text{ or } R = 14 \text{ megohms.}$$

A safe general rule is that the insulation resistance should be approximately 1 megohm for each 1,000 volts of operating voltage with a minimum value of 1 megohm.

No new apparatus should have an insulation resistance of less than 1 megohm.

Insulation resistance of apparatus in service should be checked periodically at *approximately the same temperature* and under similar conditions of humidity to determine possible

deterioration of the insulation. When such measurements made at regular intervals as a part of the general maintenance routine show wide variations in insulation resistance, the cause should be determined and abnormal conditions should be corrected before an insulation failure occurs.

Dielectric Strength.—The purpose of the dielectric tests is to determine that insulation will withstand voltage stresses occurring during normal or assumed abnormal conditions of operation.

The assurance provided by a dielectric test may warrant the risk involved in applying it as *Preventive Maintenance* prior to a critical period of operation. The damage resulting from an insulation failure at the time of a properly applied dielectric, or high voltage test, is likely to be very little compared to the loss caused by a breakdown while apparatus is carrying an important load.

As an example: In the chemical industry such a breakdown might ruin the product of many days operations; and more days would then be required to bring up the process to the stage at the time of the failure, even if other electrical apparatus were immediately available. Furthermore, the additional cost of repairs resulting from the failure under load must be given consideration.

The insulation of electrical apparatus that has been repaired or reconstructed should be given a dielectric test.

Samples of insulating oil taken from transformers, induction regulators and circuit breakers at regular intervals should be tested for breakdown value.

Dielectric tests are a part of the regular test procedure of manufacturers of electrical apparatus. *The Standards of the American Institute of Electrical Engineers* are the accepted authority for these tests.

Dielectric tests are generally made with alternating current of commercial frequency (25-60 cycles) for a period of 60 seconds.

Direct current high voltage tests are being applied to a limited extent in testing insulation. Their principal use is for determining the dielectric characteristics of cables and for laboratory work. Research is being carried on to develop these tests for the commercial testing of electrical apparatus insulation. A decided advantage of high voltage direct current for maintenance insulation testing would be in the greatly reduced weight and size of the equipment required for testing large, high voltage apparatus.

Dielectric test voltage values have not been established for apparatus that has been operated in commercial service, nor is there authorization for dielectric tests for windings that have been repaired. It is rather general practice, however, to apply from 65% to 75% of the authorized test voltage for new apparatus. As many of the conditions affecting such tests are extremely variable, the decision concerning procedure is generally made by the maintenance engineer.

Motor Efficiency and Losses

General.—The purpose of obtaining the characteristic curve of a machine is to get a permanent record of its behavior by which to judge its performance and suitability for different applications. The availability of a motor for any particular duty is determined almost entirely by two factors—the variation of its *torque* with *load* and the variation of its *speed* with *load*.

The more common characteristics of motors obtained by tests are:

1. Efficiency, torque and speed as a function of current.
2. Saturation curves.
3. Speed torque curves (series, shunt, cumulative and differential compound).

In addition, friction, core-loss and miscellaneous load and heat-run tests are frequently made.

Efficiency of Generators and Motors.—The efficiency of generators or motors is the ratio of its useful *output* to its *total input*. It is written

$$\text{Efficiency} = \frac{\text{output}}{\text{input}} \quad (1)$$

This may also be written:

$$\text{Efficiency} = \frac{\text{input} - \text{losses}}{\text{input}} \quad (2)$$

or

$$\text{Efficiency} = \frac{\text{output}}{\text{output} + \text{losses}} \quad (3)$$

Equations (1) and (2) are used for efficiency measurements on direct current motors, whereas equation (3) is used for efficiency measurements on direct current generators.

If the losses in a motor be summarized, equation (2) may be rewritten, and the efficiency is given by

$$\eta_m = \frac{V_t I_L - (V_f I_f + I_s^2 R_s + I_a^2 R_a + P_{sp})}{V_t I_L} \quad (4)$$

Where V_t = terminal voltage

I_L = line current

$V_f I_f$ = copper losses in the shunt field

$I_s^2 R_s$ = copper losses in the series field

$I_a^2 R_a$ = copper losses in the armature

P_{sp} = stray power losses

Using the foregoing abbreviations the efficiency for a generator from equation (3) is

$$\eta_g = \frac{V_t I_L}{V_t I_L + (V_f I_f + I_s^2 R_s + I_a^2 R_a + P_{sp})} \quad (5)$$

Terms within the parentheses in equations (4) and (5) are the combined total losses in a motor and generator respectively.

The *copper losses* in a machine may readily be calculated in each case, the stray power losses (P_{sp}) represented by frictional losses of bearings and brushes, windage resistance, hysteresis and eddy current in the armature and pole faces, can, however, not be calculated directly, as they are all some function of speed or flux, or both.

The Prony Brake.—If the output of a motor is measured by a Prony brake, fig. 11, then the output measured in horsepower

$$HP^* = \frac{2\pi(FR)N}{33,000} \quad (6)$$

but since (FR) is the torque T of the motor in ft.-lb. it follows that

$$HP = \frac{2\pi TN}{33,000} \quad (7)$$

*In developing the expression for the horsepower converted into heat, let (R) represent the radius of the pulley in feet, and (F) the force in lbs. supplied at the surface of the pulley. Then when the pulley completes one revolution, the force (F) moves a distance of $(2\pi R)$ feet, and therefore, $F(2\pi R)$ foot pound work is done. When the pulley rotates at (N) revolutions per minute $FN(2\pi R)$ work is done, but since one horsepower is developed for every 33,000 foot pounds of work done per minute, then to convert foot pounds per minute into horsepower, the horsepower must be divided by 33,000 or

$$HP = \frac{2\pi FRN}{33,000} \text{ (as written above).}$$

Dynamometers.—These are generally of two classes, namely,

1. Absorption.
2. Transmission.

They differ mainly in that while an absorption dynamometer absorbs the total power delivered by the motor being tested, the transmission dynamometer absorbs only that part represented by friction in the dynamometer itself. A typical absorption dynamometer is represented by the Prony brake previously described.

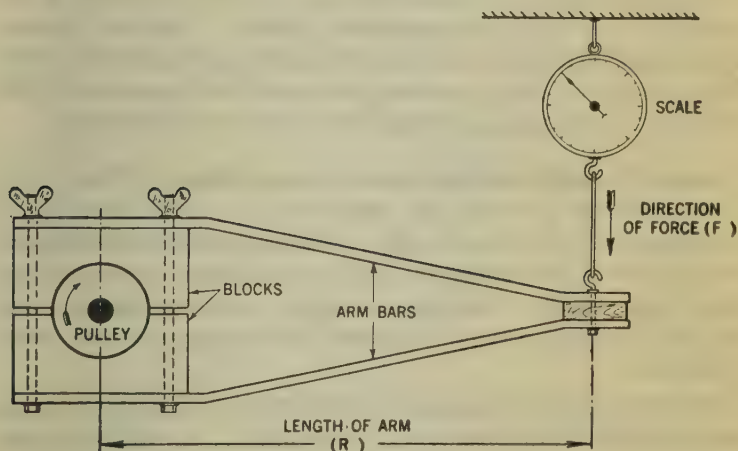


FIG. 11.—Schematic representation of Prony brake. Due to the heat generated between the wood blocks and pulley surface, it is generally necessary to introduce cooling water by means of specially designed pipes when large amounts of power are measured. In the illustration it is obvious that the product of the scale reading and the length of the arm produces a torque which is equal to and opposed to the torque (T) produced by the motor, that is, $T = F \times R$.

The principal forms of transmission dynamometers are the torsion and the cradle types. In the former type, the deflection of a shaft or spiral spring, which mechanically connects the driving and driven machines, is used to measure the torque. The spring is calibrated statically by noting the angular twist corresponding to that of a known weight at the end of a measured lever arm perpendicular to the axis.

The angle when testing may be measured by electrical or optical methods.

In the cradle dynamometer type the power is absorbed electrically by a generator whose shaft is connected to the motor under test.

The term cradle is derived because of the mounting of the generator in a trunnion supported cradle. The pull exerted between the armature and the field tends to rotate the latter. This torque is being counter-balanced and measured with weights moved along an arm in the conventional manner.

Speed Torque Characteristics; Series Motor.—This curve is obtained by running the motor at its rated voltage and absorbing the power by a brake. Readings of torque and speed are recorded. The speed should not be allowed to exceed four times rated speed. The motor, under a moderate load to prevent its running away, is started by cutting out its series resistance.

The load should be gradually reduced by adjusting the brake until the maximum safe speed is recorded. At this point the speed and torque should be recorded. Then the load should be increased step by step, taking simultaneous readings of *speed* and *torque*. The load should be increased until either the motor stops or the current exceeds the heating limit of the motor, which for a few minutes may be taken as two or three times the normal full load current. An ammeter of sufficient

rating should be connected to record the current. A voltmeter is required to make certain that the impressed voltage remains constant and equal to the rated voltage of the motor. The readings of the speed in *r.p.m.* are plotted against at the torque in pound-feet.

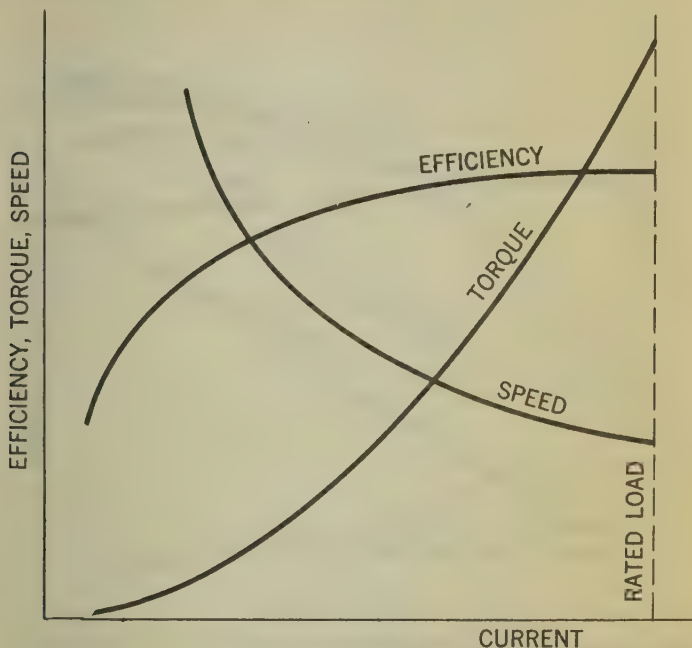


FIG. 12.—Characteristic curves of series motor.

Speed-Torque Characteristics; Shunt Motor.—The motor is started by an ordinary shunt motor starting rheostat, the brake being adjusted to absorb no power and the speed of the motor measured. Then the load is increased, step by step, until the maximum safe overload or breakdown torque is reached. A

line ammeter and voltmeter to record the current and voltage respectively are required. The readings of the speed in *r.p.m.* are plotted against the torque in foot-pounds.

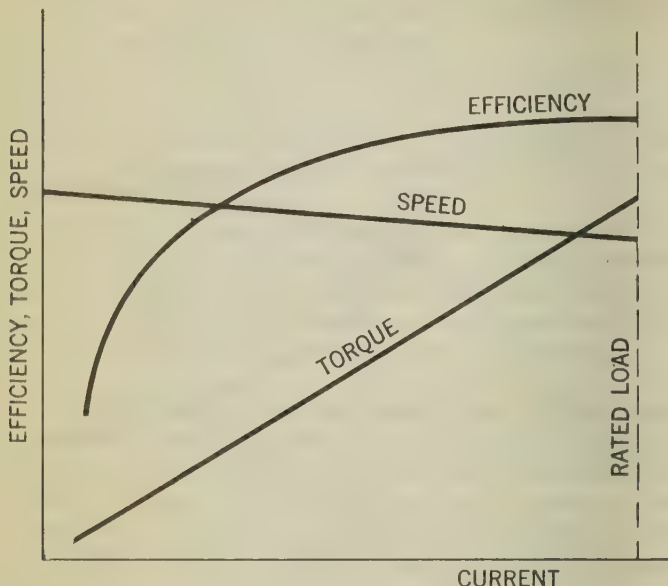


FIG. 13.—Characteristic curves of shunt motor.

Speed Torque Characteristics; Compound Motor.—If in a compound wound motor the series field is connected so that it aids the shunt field, the motor is said to be *cumulatively-compounded*; if on the other hand, the series field is connected to oppose the shunt field, the motor is said to be *differentially-compounded*.

In a *differential-compound* motor, the series field opposes the shunt field so that the magnetic flux is decreased when the load is applied. This results in speed remaining substantially constant or even increasing with an increase in load. This speed characteristic is obtained with a corresponding decrease in the rate at which the torque increases with the load.

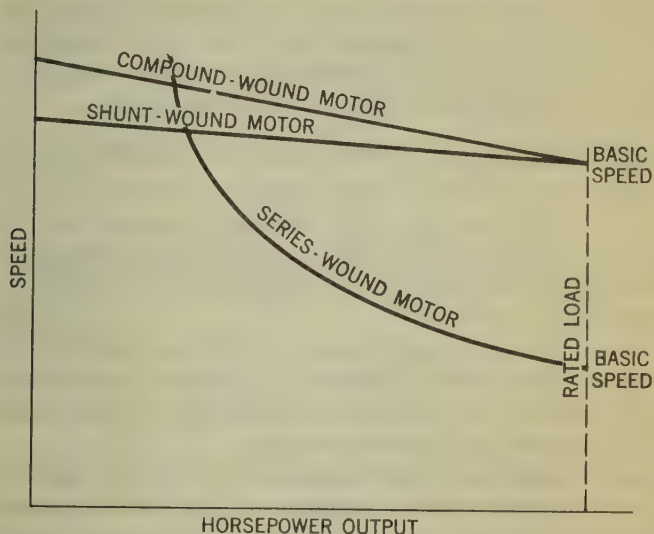


FIG. 14.—Speed output curves of direct current motors.

The *cumulative compound* motor has characteristics which are a combination of shunt and series characteristics. As the load is applied, the series ampere-turns increases the magnetic flux, causing the torque for any given current to be greater than it would be for a shunt motor. On the other hand, this increase in flux causes the speed to decrease more rapidly than it does in the shunt motor. It develops a high torque with a

sudden increase of load, and has a definite no-load speed and has no tendency to run away when the load is removed.

The speed torque curves are obtained in a manner similar to that previously described for the series and shunt motor.

Efficiency, Torque and Speed as a Function of Current.

These are standard curves, which are generally required for series motors used in railway and hoist service. They may also be taken for shunt and compound motors, but a separate set is required for each setting of the shunt field rheostat.

Loading Back Tests.—When a machine is loaded on a brake or a rheostat, the total power input is converted into heat and is, therefore, wasted. This wastage of power, particularly in the case of large machines, is a considerable expense, and may in some cases exceed the available amount of power in the testing room or factory.

To overcome this loss of energy various methods have been devised. These consist commonly in loading one machine on another, and in this way only the losses in the two machines need be supplied by the power source.

Thus, for example, it may be pointed out that during the late War a considerable amount of power was obtained by connecting generators to aircraft motors which had to be test run for a considerable number of hours. Prior to this innovation this considerable power was wasted in heat absorbing machinery of various types.

Kapp's Loading Back Method.—The connection arrangement for this test is shown in fig. 15. As indicated the two machines are connected in parallel and are also mechanically connected by means of a belt. One machine is run as a motor and the other as a generator.

The output of the generator is "fed back" to the motor, so that the supply source has to supply only the difference between the input to the motor and the output of the generator.

In starting the test, the switch connecting the two machines is opened, and the motor is brought up to speed in the usual manner. Through the belt connection, the other machine is now being run as a generator. The generator field rheostat is then adjusted until its voltage becomes equal to that of the supply source. The switch is then closed. From the indication of the various instruments shown, the losses may easily be determined, and from this the efficiency, by a simple application of Ohm's law.

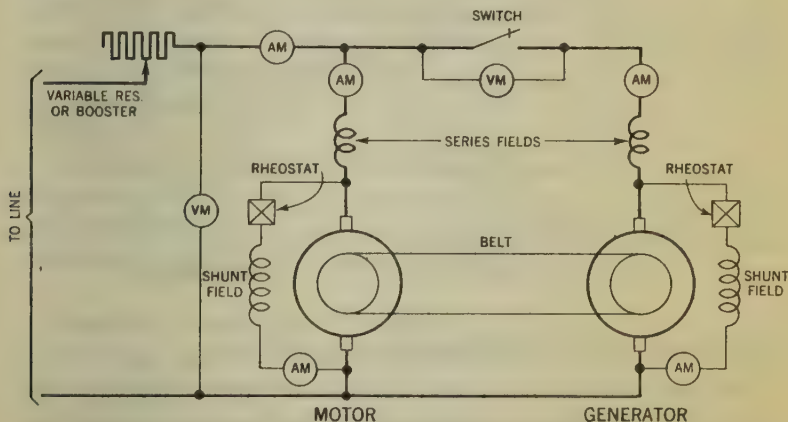


FIG. 15.—Diagram of connections for *Kapp's loading back test*.

When the two machines are identical in construction, an approximate value of the efficiency of each may be obtained by measuring in addition to the terminal voltage, the current

supplied by the power source. The total losses in the two machines are then equal to the potential across the circuit multiplied by the total current supplied. It follows, that if the current in the two machines are equal, and also their back electromotive forces, the total power loss in each machine is simply $EI/2$.

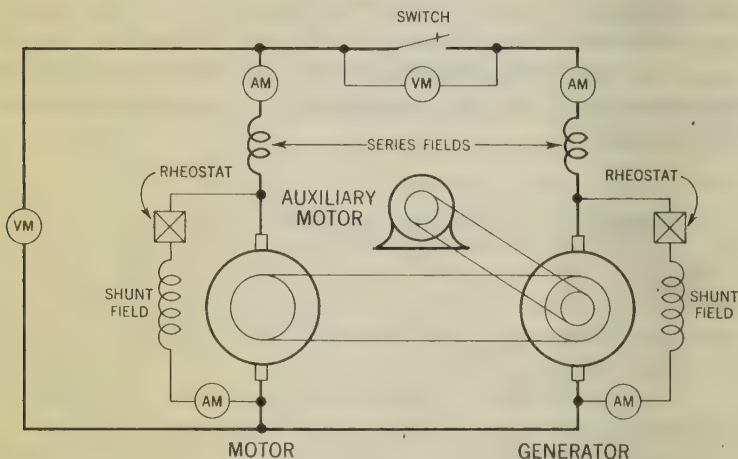


FIG. 16.—Diagram of connections for Hopkinson's loading back test.

In actual practice, however, this is not exactly true since the back electromotive force on the motor will always be less than that of the generator. Also the armature current of the motor will always be greater than that of the generator. It follows, therefore, that the core loss of the motor will be less than the core loss of the generator, and the armature (I^2R) loss of the motor will be somewhat greater than the armature (I^2R) loss of the generator.

From the foregoing, it is clearly evident that only as a rough approximation may the loss in each machine be taken to equal $EI/2$.

Hopkinson's Loading Back Method.—This loading back test method differs principally from the previously described Kapp's method in that instead of supplying the losses in the two machines electrically, the supply losses are supplied mechanically by an auxiliary motor. The connections are as shown in fig. 16. The auxiliary motor is used to supply all the losses, the current in the armatures are being circulated by weakening the field of one machine and strengthening that of the other. It should be observed, however, that the core losses in the machines are different, because the fields have different excitations. It follows, therefore, that while this method is quite satisfactory as a regulation and heating test, it is not satisfactory for efficiency tests.

Saturation.—In order to ascertain the characteristics of the magnetic circuit, a test known as a saturation test is made. The characteristic curve may be obtained by either of the following methods: Generator saturation or motor saturation.

Generator Saturation.—To obtain a saturation curve by this method, the machine is driven at normal speed as a generator. The brushes of direct current machines should always be set on neutral, and the machine run at its normal rated speed.

In taking the saturation curve on polyphase alternating generators, a reading of the voltage across each phase must be taken at normal field current, to see if all phases are properly balanced. If they do not balance, they must be made to do so. With synchronous converters, careful readings must be taken of direct voltage as well as the alternating voltage, between all

phases with the field excitation giving normal voltage. The phase voltages must also be closely balanced.

The usual method of taking the generator saturation curve is to hold the speed constant, and then increase the field current step by step until full field excitation voltage has been reached, taking simultaneous readings at each step of armature voltage, field voltage, and field amperage. About twelve points are sufficient. Four readings should be taken from zero field to 90% normal rated voltage of the machine. Five points should be taken between 90% and 100% normal rated voltage, taking one of the points at the normal rated voltage of the machine. Three points should be taken between 110% normal rated voltage to full field on the machine.

After reaching the maximum value of the field current, without opening the field, reduce the current gradually in four or five steps, and again take readings to determine the value of residual magnetism at various points along the curve. Special care must be taken to insure accurate readings at and above normal voltage, for in alternating current generators this is the portion of the curve used for calculating the regulation load.

On separately excited high voltage, direct current generators, the saturation curve should be carried only to 25% above the normal rated voltage.

Motor Saturation.—When it is inconvenient or impossible to drive the machine as a generator, a motor saturation curve may be made. For this case, the machine is operated as a free running motor. The driving power must be furnished from a variable voltage circuit. A certain voltage is impressed upon the armature and the motor field increased or decreased, in the case of direct current machines, to give normal speed, and a record made of armature voltage, armature amperage, field amperage, field voltage, and speed. The starting voltage

should be at least 50% lower than the normal rated voltage of the apparatus. The applied voltage of the armature should be increased by steps to 25% above normal value, and the field increased correspondingly to keep the speed constant, the same readings being recorded at the various steps as before. Readings should also be taken at three or four points as the impressed voltage and field current are lowered to approximately the values at the beginning of the test.

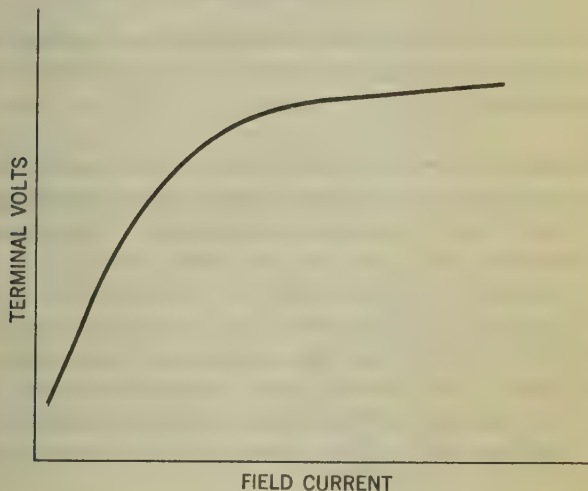


FIG. 17.—Typical saturation curve of shunt motor.

Care must be taken in testing direct current apparatus, because unstable electrical conditions may develop, and excessive speeds result. The circuit breaker, in the armature circuit of the motor driving the machine, must be accessible to the tester reading the speed.

On alternating current apparatus, the machine is run as a motor and the impressed voltage varied as already described.

The speed is independent of the motor field in this case, and instead of regulating the motor field for speed, it should be regulated to give minimum input current at each voltage. Readings should be taken of each voltage impressed, armature amperage, field amperage, and field voltage. With induction motors, it is only necessary to impress variable voltages at constant frequency and record readings of impressed armature voltage, armature amperage, and speed.

A curve should be plotted, using armature voltage as ordinates and field amperage as abscissae. Fig. 17 shows a typical saturation curve.

Core Loss.—There are two methods commonly used to measure the core losses of rotating direct current apparatus and alternating current synchronous apparatus. They are as follows: "Running light" core loss, and belted core loss.

The following conditions must be obtained with the direct current apparatus in order to give satisfactory results: The brushes must be shifted on the commutator to the mechanical neutral point. The driving power should be supplied from a variable voltage source that is not subject to sudden fluctuation. Readings must not be taken when the rotating parts are accelerating or decelerating.

Running Light Method.—This test is made by running the machine free, as a motor. It is made on most direct current generators and motors which are given a running test, and occasionally on alternating current synchronous apparatus.

When running any direct current machine as a motor, the following procedure should be followed: Set the brushes on mechanical neutral. Be sure that the water box for starting is plugged across the main switch, that the main switch is open,

and the blade of the water box is way up. Plug the power to the armature, bring the supply voltage up, close the breaker, and lower the blade of the water rheostat slowly, watching the reading on the line ammeter. If the machine does not start to rotate at a value of current below full load, take off the power and investigate the cause. When the machine is running at rated voltage, close the line switch and raise the blade of the water box again. If the machine runs too fast at normal voltage, pull off the power. The connections should be carefully checked to see that the field is wired properly. It may be that the field is connected directly across the main switch. If such is the case, the field current will fall rapidly as the starting resistance is cut out and the motor will speed up. To test for incorrect wiring in the field, observe the field voltage during starting, because it will drop if the field is incorrectly connected.

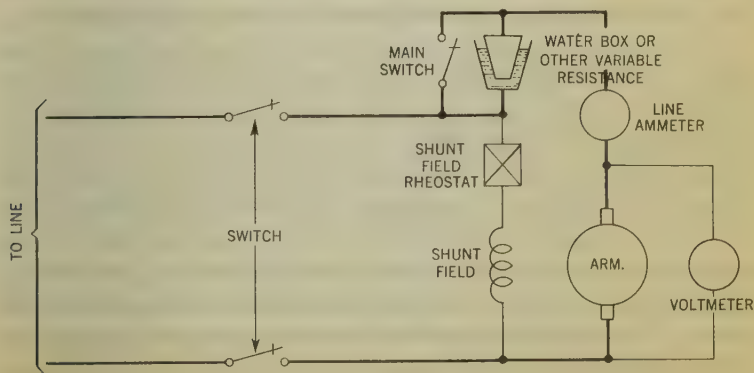


FIG. 18.—Showing connections for *running light* test when applied to a shunt machine.

When running light tests are made on generators, the observations must be made with full load field flux. The potential applied to the armature must be equal to the normal rated voltage of the generator, increased by the IR drop under full load. The IR drop is taken as 4% of the normal voltage for both motors and generators. With this voltage impressed, the field current is varied until normal speed is obtained, when careful readings must be made of armature current, armature voltage, field current, field voltage and speed.

If the machine in test is a direct current motor, the voltage applied to the armature should be equal to the normal rated voltage of the motor, less the IR drop under full load. The field current is then adjusted to give normal speed, and electrical readings taken as previously outlined for direct current generators.

The power supplied to machines running free will equal that absorbed in bearing friction, brush friction, windage and core loss, when the armature I^2R losses have been subtracted.

In making records of these tests, the testing record must clearly show whether the running light current consists of the armature current plus the shunt field current or whether it is the armature current alone. To check this point, open the armature circuit with the shunt field circuit closed and note whether any current is indicated on the ammeter which reads the power supplied. If no current is indicated, the reading indicates the armature current alone, otherwise, the running light current is equal to the sum of the armature and field currents. To obtain the running light core loss test, the machine should operate as a shunt motor.

For series wound motors, the field should be separately excited and extreme care should be taken to see that the motor does not lose its field.

In order to obtain running light core loss upon alternating current synchronous machines (a class in which synchronous converters are not included because the core loss test on these machines is similar to that on direct current machines), they should be operated as synchronous motors at the proper frequency and rated voltage. For the best results, both frequency and voltage must have a steady value.

With normal voltage on the armature, the direct current field should then be varied until minimum armature current is obtained. Readings should be then taken of the current and voltage of all the phases. At minimum input current, unity power factor is obtained and, therefore, the power to drive such machines will be the volt-ampere input. Wattmeters may be used in addition, to check the volt-ampere readings. This measurement includes friction and windage losses, together with open circuit core losses, plus the I^2R loss in the armature. If the value of the core loss need not be separated from the other losses, the test is useful for checking up load efficiency.

On motor generator sets, unless otherwise specified in instructions, the following running light tests should be made: With direct current brushes down, running at rated speed from direct current end with line voltage 4% high as for any generator, and no field on synchronous motor, take and record readings of line voltage and current, field voltage and current, and speed.

Continuing to hold line voltage and speed, bring up the field on the synchronous motor until normal voltage on armature is obtained. Take and record readings of synchronous motor armature volts, field volts and amperes, together with another set of input readings on generator as before. The difference of these two sets of input readings will be the core loss of the synchronous motor.

Belted Core Loss Method.—By means of the belted core loss method, the core loss can be separated from the bearing friction, brush friction and windage. A small direct current motor is used to drive the machine under test, as a generator at its rated speed. A belt drive between these machines is most commonly used, but whenever great accuracy or a high speed is necessary, a direct drive by means of a coupling is often used.

The driving motor for this test should be such that good commutation is obtained for all the loads required by the core loss test, with a fixed setting of the brushes. With the maximum volts on the machine under test, it should carry not more than 100% of its normal rated capacity.

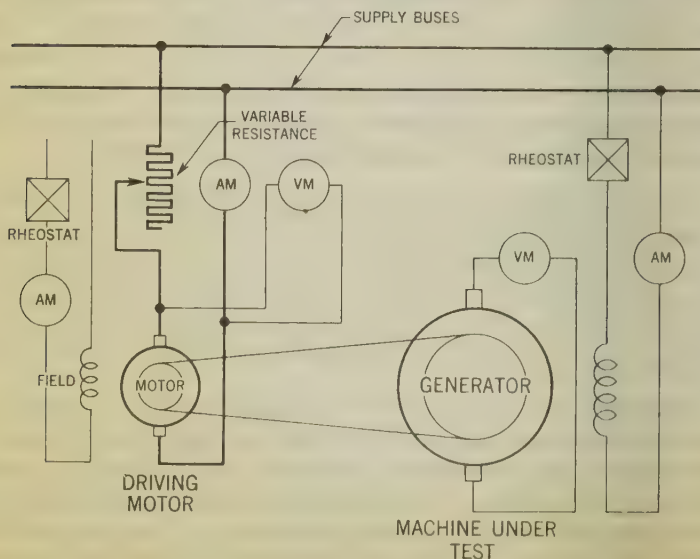


FIG. 19.—Diagram showing connections for belted core loss and friction test.

Ordinarily, a good rule to follow is to select a motor the rated capacity of which is approximately 10% of the rated output of the machine under test. When the brush setting to give the best possible commutation at all loads has been obtained, the brushes should be left in a position that will give the motor a slightly falling speed characteristic. With the brushes in this position, the voltage applied at the armature will have to be increased as the load is applied in order to maintain constant speed. The commutator surface should be in first class condition and should have the brushes closely fitted to it.

The belt should be of minimum width and weight to carry the load without slipping. When testing motor generator sets, synchronous converters and other machines that do not require belts in practice, the tension of the belt must be kept as low as practical so that the bearing friction is not increased by the belt pull. Endless belts should always be used in preference to laced belts.

The diameter of the pulleys should be selected so that the driving motor will run at or near its normal rate of speed when the motor under test is running at its normal speed.

The driving motor should have its field separately excited from a constant source, and other wiring so arranged that readings may be taken of armature current, armature voltage, field current, and speed. The volt wires should be firmly attached by the brushes on two adjacent studs. The brushes so used should be insulated from the brush holders so that the true armature voltage may be obtained.

The machine under test should be wired as a separately excited generator with provision for reading armature voltage, field voltage, field current, and speed.

The tests should be carried out as follows: The field of the driving motor should be adjusted to about normal value and

held constant, and the speed regulated by varying the voltage applied to the armature terminals. Careful readings should be made to make sure that no belt slipping occurs, by taking simultaneous readings of the speed of both the driving motor and the machine under test: (a) with no field on the machine under test, (b) with normal field excitation. The two readings of speed should be identical. The machine should be run a length of time sufficient to allow the friction to become constant. This will be the case when the input to the driving motor remains constant when driving the machine under test without any field excitation.

Throughout the entire test, readings must be taken at absolutely constant speed when the rotating parts are neither accelerating nor decelerating. The readings should be taken as follows: (a) take the input of the driving motor, with no field on the machine under test and with all brushes down on the commutator; (b) take the input, with all brushes raised and with no field on the test machine. The difference between these two readings is the brush friction.

Then, starting with zero field on the machine under test, and with the brushes raised from the commutator, observations of input to the driving motor should be recorded at various values of field up to that which will give 125% of normal voltage; and at least half of the readings should be taken between 90 and 110% of normal voltage.

The friction reading with zero field excitation on the machine under test should be repeated at least three times during the process of the test; namely, at the beginning, again near the mid-point of the curve, and finally at the end of the test.

The driving motor should then be disconnected and a running light reading taken as follows: Without changing the brush lift, hold the same field current that was held during the core loss

test and take a reading of the input to the motor to give the same speed that was read on the driving motor at the beginning of the test.

The armature voltage should be lower than for any other reading taken during the core loss test.

To check the results of the core loss as the test proceeds, the power input to the driving motor required by the core loss at a given excitation should be plotted against volts armature generated.

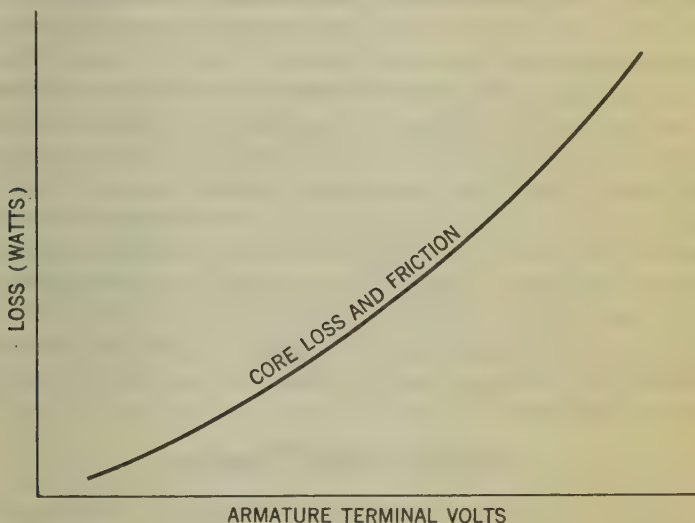


FIG. 20.—Typical core and friction loss characteristics.

Correct the motor input at various field strengths by deducting the I^2R loss in the armature of the driving motor, and subtracting the power input to the driving motor with zero field on the machine in test. The core losses left correspond to the various field strengths. By subtracting the running light input

to the driving motor from the input at zero field on the machine in test, the bearing friction and windage losses of the machine under test are obtained.

On series motors, core loss tests should be taken at several different speeds covering the range of the speed curve. The method used is identical with that previously described.

The synchronous alternating current machines generally have loss measurements as previously outlined, an open circuit, and also with the armature of the machine under test short-circuited. In the latter case, the increase in power supplied by the driving motor over that required by the friction loss is plotted as ordinates against the armature amperage as abscissae, or the open circuit armature voltage due to a given excitation. A curve is obtained similar in character to the open circuit core loss curve. Such test is commonly known as short-circuited core loss. In making this test, careful measurements must be made of the resistance of the short circuited armature circuit, including all leads. Observations should be made starting at 200% normal current value and reducing by steps to zero current. Several thermometers should be placed on the stator winding and readings taken of temperature after each step on the core loss curve.

Heat Run Tests

Heat runs are taken primarily to determine the amount of temperature rise on the different parts of the machine while running under a specified load. This rise in temperature is measured by either the rise in resistance of the current carrying part, by means of the thermometer, or by both. The results as obtained by the rise in resistance, as a general rule, are used only as a check on the results obtained by reading thermometers placed on the different parts, the temperature rise of which it is desired to determine.

The average temperature of the winding is obtained from the resistance measurements by using the following equation:

$$T = \frac{R}{r} (234.5 + t) - 234.5$$

Where T = hot temperature in deg. C.

R = hot resistance.

r = cold resistance at temperature t .

t = cold temperature of winding in C.

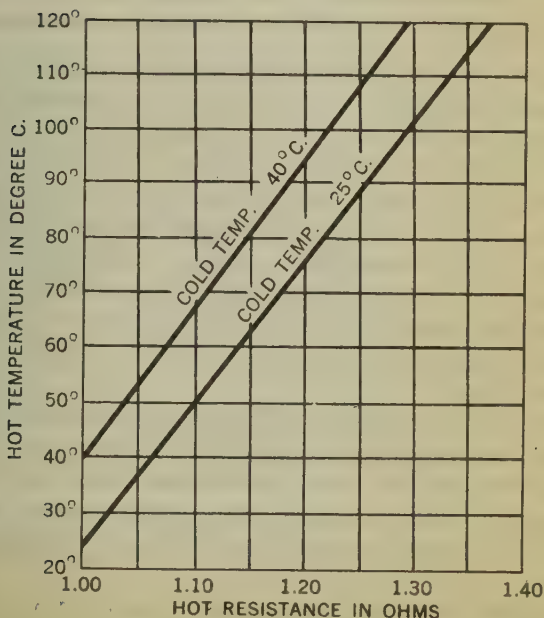


FIG. 21.—Curves showing determination of temperature from resistance measurements.

As an example: Assume that the cold resistance is 0.50 ohm at 25° C. and the hot resistance is 0.61 ohm. Then:

$$\begin{aligned} T &= \frac{0.61}{0.50} (234.5 + 25) - 234.5 \\ &= 82^{\circ}\text{C} \end{aligned}$$

The temperatures measured by detectors or by the change in resistance are generally higher than thermometer measurements and are closer to the true hottest spot temperature in the machine. For this reason, the Standards permit higher observable temperature rises when measured in this manner.

Special copper leaf brushes are commonly used for measuring the voltage on fields of alternators and synchronous motors by the volt-ampere method. The resistance by the volt-ampere method must be made to check within 1% of the Wheatstone bridge resistance measurement before the machine is started the first time. Three readings of volt-amperes should be taken at 20, 25 and 30% normal field voltage, with thermometers on two poles to be read at each of the foregoing voltage readings.

Self-excited, direct current machines must be checked, as described previously, immediately after the voltage is brought up the first time.

As the heat run progresses, the temperature rise of the field should be calculated and recorded at the same time the thermometer readings are taken. All meters to be used on a heat run should be checked against other meters before the run is started. The same meters must be used throughout any given test.

Thermometers should be carefully examined for a broken mercury column before being used and should not be inverted or placed on a machine so that the bulb is at a higher level than the other end. Before starting a heat run, thermometers

should be placed on the stationary accessible parts of the machine. Each thermometer should be attached with the bulb in contact with the part of which the temperature is required and should have the bulb covered with an amount of putty sufficient to secure it to the machine and to shield it from the surrounding air. Extreme care must be exercised regarding the amount of putty used, as too much putty is as bad as too little. Just enough should be used to do the work required. There should be no restriction of the natural windage of the machine, or radiation from the coil of which temperature is being measured.

Thermometers which are to register the temperature of the air ducts should be placed so that the bulbs cannot make contact with the iron laminations while the machine is running. Thermometers which are liable to be shaken off by continued action of windage, or vibration should be securely fastened to the machine. When placing thermometers on field coils care should be taken to see that they are not placed on the fiber strips protecting the outside terminals. These fiber strips run from one terminal to the other and from a non-conducting wall between the coil and its outside insulation, and thus do not represent the true temperature of the coil. Coils above the horizontal center line of the machine should be used as the top of the machine. They are usually somewhat hotter than the bottom coils. On small machines, two thermometers will be sufficient on the coils, but larger machines should have at least four.

One thermometer will be sufficient on the frame of small machines, but two should be used on large units. At least two thermometers should be used on the laminations and ducts of small machines, and four or more used on the larger machines.

Any large machine requiring considerable floor space should have the room temperature taken at four or more nearby points.

These thermometers should be placed about six feet from the base of the machine and at the elevation of the center line of the machine. These thermometers should be placed two together; one set in an oil cup designed for this purpose, the other set should hang in the air to record the air temperature. All of the room temperatures, whether they are placed in air or oil, should be so located that they are not affected by the windage and radiation of the machine.

The machine should be shielded from currents of air coming from adjacent pulleys, belts and other machines, as unreliable results are obtained when this is not done. A very slight current of air will cause great discrepancies in the heating results. Consequently, a suitable canvas screen should be used to protect the machine under test when necessary. Great care must be used, however, to see that the screen does not interfere with the natural ventilation of the machine under test. Care should always be taken to see that sufficient floor space is left between machines to allow free circulation of air. Under ordinary conditions, a distance of six feet is sufficient.

Immediately after the heat run is started, various checks should be made. (1) On all heat runs where meters are connected in both the output and input circuits, especially motor generator sets and converters, the power output readings plus the losses of the apparatus under test must equal the power input readings. (2) On all synchronous machines, the power factor specified in the instructions should be held and checked against the phase characteristic on motors and saturation on generators. In such cases the field current held during the heat run should be greater than the unity power factor field current.

CHAPTER 14

Commutator Maintenance

General.—The most important factor, and the one upon which the success or failure of any D.C. machine and commutator type A.C. machine depends, is commutation.

Regardless of any other good features a machine may have, it is of no commercial importance unless it can be made to commute successfully.

Satisfactory commutation means operating under reasonable service conditions without excessive sparking, burning of commutator bars or brushes, or other conditions requiring excessive maintenance.

Assuming that the design of a machine is such that good commutation is to be expected, one of the surest means of securing satisfactory operation is through maintaining the surface of the commutator in good operating condition. Generally this means that the commutator surface should be *smooth, concentric and properly undercut*.

Poor Commutation and Its Causes.—In machines used for industrial and power applications, commutators may become rough through overloading which produces excessive sparking or burning and overheating.

In *railway work*, an additional cause of roughness is over-speeding of motors. Over any considerable period of time any

of these abnormal conditions may exist more or less frequently, depending on the severity of the service. As a poor surface becomes cumulatively worse, a point is reached where more satisfactory operation, and less frequent brush replacement, can be obtained by placing the surface in first class condition.

Commutator roughness is usually characterized by an abrupt change from one bar to the next as distinguished from an eccentric commutator in which there is a very gradual change in the surface where the commutator might be said to be egg-shaped. Variations from one bar to the next of as much as one ten-thousandth of an inch are sufficient to cause a commutator to perform badly, break brushes or cause excessive brush wear on high speed commutators.

Roughness of a commutator surface can be detected by placing a pencil on a brush while the machine is rotating. Care should be taken to stand on a board or insulating platform of some kind, so as not to touch any metal part of the machine, and to use a wooden pencil if the machine has voltage on it. The surface of a commutator should be concentric within one-thousandth of an inch on commutators whose peripheral speeds are around 5,500 feet per minute. For peripheral speeds in the neighborhood of 9,000 feet per minute, commutators should be concentric to within one-half a thousandth of an inch, which is about the practical limit for grinding.

Slow speed, large diameter commutators will operate successfully with greater eccentricity than mentioned previously because the angular velocity is low and the brushes can follow the surface, but it is poor practice to operate even very slow speed commutators with an eccentricity greater than three-thousandths of an inch as this may be enough to cause side wear of the brushes. The concentricity of a commutator can be checked with a dial gauge mounted on a brush.

Truing of Commutators

Resurfacing Methods.—Economical maintenance of commutating equipment is dependent in no small measure upon the care used in preparing the *commutator surface* and upon the attention given thereafter in *keeping the surface in good condition*.

It is important that the commutator surface be inspected at regular intervals and frequently enough to insure surface faults being detected in the early stages of formation. Faults can usually be corrected at such time with little expense or loss of time. However, surface faults such as *bar burning*, *high or low bars*, *high mica* or *flat spots* tend to become more serious with time, and often at an accelerating rate. Unless corrected when first observed, they may necessitate a shut down of appreciable duration and involve expensive repairs.

Generally there are three methods commonly employed in resurfacing of commutators. They are:

1. Sandpapering.
2. Hand stoning.
3. Grinding and turning.

The method to be used in truing of commutators depends largely upon the condition of the individual machine, that is, the amount of damage to be corrected, the available tools, the amount of time the machine can be removed from service, size of machine, etc.

Sandpapering.—This is a satisfactory method of removing deposit from a commutator surface, correcting roughness or reducing high mica, providing the accurate contour of the surface has not been disturbed. However, sandpaper cannot be depended on to remove flat spots even of small extent.

While it may appear to eliminate them, the effect is merely to broaden out the spot so that it is no longer apparent to the eye. Such a condition will have to be corrected by stoning or, if spots are very wide, by grinding or turning. In bad cases of high mica a stone will also be found superior to sandpaper.

In sandpapering a commutator do not use a paper of too coarse grain. It is better to select a rather fine grain and take longer to do the work. In this way deep scratches will be avoided and subsequent operation improved. Sandpapering is considered by some engineers as the best means of polishing a commutator after truing by some other method. When sandpaper is used for this purpose a very fine grain should be selected. It is good practice when applying sandpaper to a commutator to first attach the sandpaper to a wood block, the face of which has been formed to the same radius as the commutator, as illustrated in fig. 1. Lateral movement of the sanding block should be slow to avoid diagonal scratches.

One of the principal objections to the use of sandpaper for cleaning a commutator is that it very rarely leaves the bars properly round. On an unslotted commutator, particularly where the mica is high, the sandpaper has a tendency to flatten the center of the bars. This can be partly counteracted by the use of a moderate amount of oil on the paper. This tends to make the mica cut more readily and reduces the cutting effect on the copper. Oil should not be used in excess or it will work into the mica, carrying particles of copper with it and short circuits may result.

On a slotted commutator, even when used on a block rounded to fit the commutator, sandpaper has a tendency to round the edges of the bars. Oil should not be used when sanding a slotted commutator as it will cause the copper dust and sand to collect in the slots while, if no oil is used, centrifugal force will throw the dry dust from the slots.

Emery paper or emery cloth should never be used on a commutator, especially when it is being cleaned with the current flowing through the armature. The reason for this is that emery is an electrical conductor and particles are likely to become imbedded between the segments and cause short circuits.

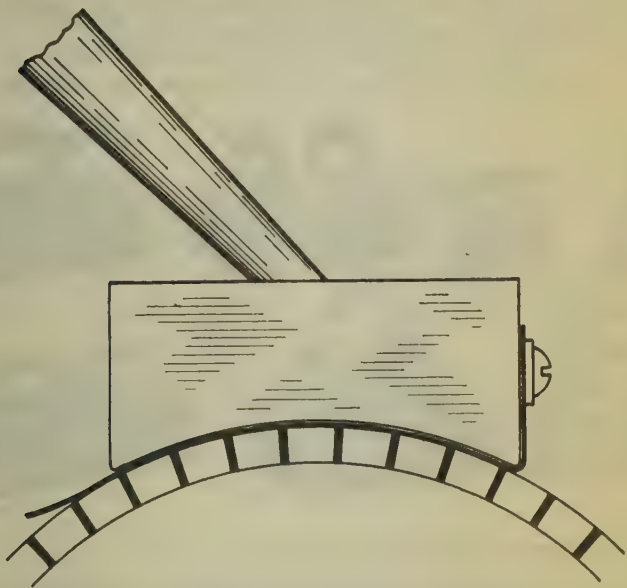
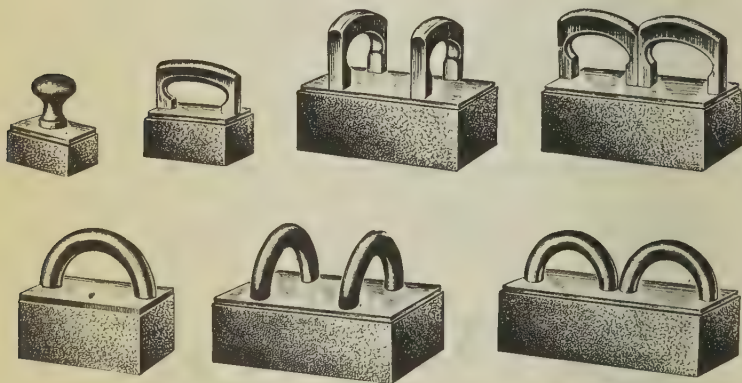


FIG. 1.—Showing method of sandpapering commutator. Sandpaper should be attached to a block formed to the curvature of the commutator.

Hand Stoning.—The tendency of sandpaper to broaden rather than remove flat spots and to distort the contour of the commutator segments results from the flexibility of the paper.

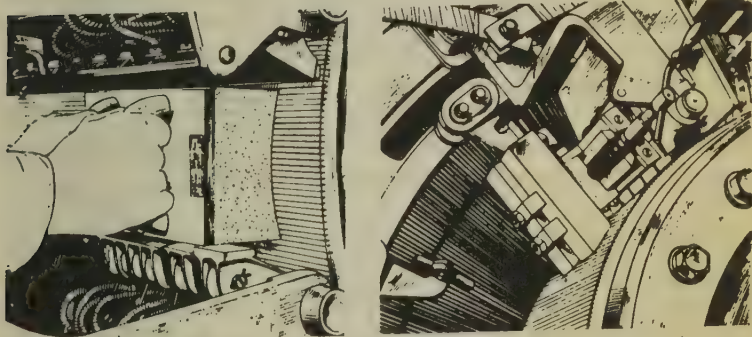
The use of a commutator stone is, therefore, recommended in preference to sandpaper. The stone presents a rigid contact surface to the commutator. It should be formed or worn to the curvature of the commutator and have a span of contact substantially greater than that of the broadest flat spot to be removed. Applied as illustrated in fig. 9, the hand stone can be successfully used to restore the commutator to true cylindrical form. The stone should be pressed firmly against the commutator and moved slowly from side to side.



FIGS. 2 to 8.—Various sizes of commutator hand stones.

Although hand stoning will restore a true cylindrical surface, application of the stone in the manner described cannot be depended upon to eliminate eccentricity. Where it is possible to arrange a solid rest for the stone, eccentricity can sometimes be corrected by using the stone as a hand-turning tool. With this method a much smaller area of the stone is brought in contact with the commutator than in the previous method.

If too large an area is in contact, the stone will slide over the surface instead of cutting steadily and the object of using this method is defeated. Hand-turning with a stone requires considerably more skill on the part of the operator than where the stone is held flat against the surface. The support must be very rigid or vibration of the stone will occur and small pits and holes be dug in the surface. Unless the operator possesses sufficient skill to use this method properly, he had better resort to grinding or turning to correct conditions that are too bad to be eliminated by a stone held flat against the surface.



FIGS. 9 and 10.—Illustrating method of grinding commutator by means of hand stone and commutator stone mounted on special rest on a brush holder stud.

When using a stone as a hand turning tool, best results will usually be obtained by running the commutator below normal speed. The speed at which the stone cuts most freely and evenly can be determined by experiment. However, it is preferable that the commutator be operated at full speed when the stone is held flat against it in the usual method of hand

stoning. Centrifugal stresses are then the same as in normal operation and the commutator surface is finished with every segment in its true operating position.

Do not use oil on a commutator stone. If grease or oil is present on the commutator surface, remove it thoroughly by wiping or sandpapering before applying the stone. Oil interferes with the cutting of the stone and often causes the face of the stone to clog with copper.

The commutator stones now on the market are almost all made from artificial abrasives. The bonding medium is of such character that as the abrasive particles become dulled from contact with the commutator, they are torn loose. This maintains a sharp cutting surface on the stone and prevents it clogging up with copper. Several grades are available ranging from very coarse to very fine. The coarse stones remove copper rapidly and are used where surface faults are deep. After a coarse stone has been used, one of finer grade should be applied to give a smooth polish to the surface.

Grinding and Turning.—While sandpapering offers a satisfactory method of resurfacing a commutator which is dirty or on which the mica is just beginning to get high, and hand stoning will remove high mica and even flat spots of considerable size, the most satisfactory method of resurfacing a commutator which is badly out of true is grinding or turning with a tool having a rigid support. All cases of eccentricity come under this head, for no hand method of finishing can entirely eliminate eccentricity in a commutator.

Before undertaking to grind or turn a commutator examine it carefully and make sure that it is tight. This should be done just after stopping the machine, while it is still hot. Other needed repairs, such as resoldering connections or repairing

insulation faults, should be made prior to the grinding or turning operation.

The commutator may be trued with the armature in its own bearings or the armature may be removed and placed in a lathe or a machine designed especially for this purpose.

When turning a commutator without removing it from the machine, the armature may be driven at the proper cutting speed by a belt from a separate motor, or the machine may itself be operated as a motor at a reduced speed. This may be done by inserting a high resistance in series with the armature so as to reduce the voltage at the terminals of the machine. If this method is used, it is necessary to insulate the tool post carefully from the rest of the machine and to see that all parts of the machine are carefully protected from copper chips. When turning the commutator in its own bearings, it is also very important to see that the turning tool or grinder has a substantial support.

When truing the commutator in a lathe, the armature may be supported on the lathe centers or on sleeve bearings. The former is simpler but the latter has some advantage in point of accuracy. In case the armature has an abnormally long shaft, steady rests should be used to avoid vibration of the shaft while turning.

The choice between these methods of truing, whether in its own frame or in a lathe, is largely determined by the size of the armature and the facilities for handling it. Armatures are generally removed to a lathe for turning unless too large.

In grinding there are some advantages in leaving the armature in its own bearings and running it near the normal operating speed of the machine. This eliminates the distorting effects of vibration and centrifugal force at the high speeds of operation. A commutator cannot be turned under these con-

ditions, however, as the surface speed is too high. Furthermore, a lathe is usually designed to give the cutting tool a more rigid support than any which can be rigged up on the base of a machine, so if the commutator is to be turned, it is advisable to remove the armature to a lathe wherever this is possible.

Before starting to turn or grind a commutator the windings of the armature, adjacent to the commutator, should be wrapped in canvas or oilcloth to protect them from copper chips and dust. When the armature is to be ground at normal speed in its own bearings, it may not be feasible to do this, but the armature should be so protected whenever possible and always when it is to be turned; otherwise chips of considerable size are practically certain to lodge in the windings and short circuits or grounds are likely to result.

In grinding there are two general methods, one with a stationary stone, the other with a revolving wheel of abrasive material.

When grinding with a stationary stone a smooth, fine-grained stone should be used, the same as is used for hand stoning. This must be rigidly clamped in a holder and provided with a substantial support so there may be no chance of the stone digging into the commutator. Some experimenting may be necessary to determine the best cutting speed. Beyond a certain speed a stationary stone will not cut smoothly and it is seldom possible to grind a commutator at full speed by this method. The best cutting speed will probably be found around 1,000 to 1,500 *f.p.m.*

Fixtures of various types are on the market designed for mounting a stationary stone on the brush rigging of a motor or generator and feeding it across the face of the commutator. Typical attachments of this kind are shown in figs. 11 and 12. Some of these attachments can be used for mounting either a

stationary stone or a steel turning tool. Such fixtures must be given rigid support to prevent chattering of the stone or tool. In some cases it may be necessary to reinforce that portion of the brush rigging to which the fixture is attached. Since the stone wears away in the course of its lateral motion, heavy cuts should be avoided and care should be taken not to give the commutator surface a keg, saddled or tapered profile. Several very light finishing cuts will help to establish uniform diameter over the entire length of the commutator.



FIGS. 11 and 12.—Showing application of grinding equipment to commutator. The attachment used to hold the stone when grinding a commutator should be accurately built and rigidly mounted.

A rotating abrasive wheel, directly mounted on the shaft of a small motor or driven by a flexible shaft, is preferred by some operators to a stationary stone, as they consider it less liable to chatter or dig into the commutator. A medium soft wheel should be used since the face will not fill up with copper as readily as that of a hard wheel. Use a light cut to prevent wear of the wheel giving the commutator a distorted profile.

A heavy cut will also tend to reproduce any eccentricity of the commutator due to unavoidable spring in the supporting rigging.

Where a commutator is badly out of true it may be necessary to take a large number of light cuts, but this is the only way it can be brought back to proper shape. Machines for this purpose are available, designed for attaching securely to the brush holder rigging. Where a home made device is prepared this question of rigid support must be given careful consideration. Speed the cutting wheel at the rate recommended by the manufacturer of the wheel used. Commutator speed will be determined by conditions. If a commutator that is badly out of true is to be finished entirely by grinding, it will be well to remove most of the eccentricity with the commutator revolving at a moderate speed. This will avoid excessive wear of the grinding wheel. After the commutator is approximately true, it may be speeded up to its normal speed so that any distortion which takes place at such speeds will be eliminated.

Final surface may be obtained by the use of a very fine abrasive wheel or fine grain sandpaper. Some manufacturers put the final surface on their commutators with a hand stone. Whatever method is used, care should be taken to eliminate all scratches, especially those in a diagonal direction on the commutator surface and to bring the surface to as near a polished condition as is possible.

In turning a commutator with a steel tool, use what is known as a "diamond-point" tool or one with a fairly sharp point. The point of the tool should be rounded sufficiently that the cuts will overlap and not leave a rough thread on the commutator surface. Use a light cut, taking several cuts if necessary to remove bad flat spots or a considerable degree of eccentricity.

This is done to avoid springing of the tool support. Furthermore, in turning a commutator with a heavy cut, the tool has a tendency to twist the segments, thus cutting deeper at one edge than at the other. This difference may be slight but less than .001 inch variation in the commutator surface is sufficient to break contact with the brush face, causing the current to jump across that point in the form of a minute arc and cause edge burning of the bars.

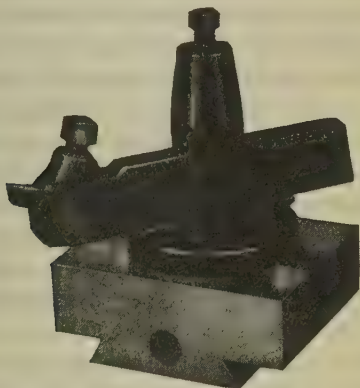


FIG. 13.—Showing typical lathe type turning tool. When using the tool the commutator must be turned over slowly, either by use of an auxiliary motor, or gear and belt reduction. On large machines, the armature may be allowed to "coast" until a safe cutting speed is reached and then the cutting operation begun. Includes a high speed tool bit, tool holder, tool post fittings and spot finished cast iron base.

The surface speed must be lower in turning than in grinding. In general, a surface speed of 500 to 600 *f.p.m.* should not be exceeded in turning. Care in obtaining a rigid support for the tool is even more important than in grinding. This is one reason why it is advisable to remove an armature to a lathe whenever possible, as a lathe is usually designed with a more rigid tool support than can be built up on the frame of a machine.

Final surfacing after turning requires more care than after grinding due to the twisting effect of the cutting tool on the segments. One method, after turning the commutator, is to grind it with a stationary stone mounted in the tool post, running the armature at as high a speed as will allow smooth cutting. It is then given a final polish with a hand stone or very fine sandpaper, the commutator running at full speed.

Grinding and turning each have certain advantages as methods of truing a commutator. Probably all things considered, better results will be obtained from grinding when properly done. Less copper will generally be removed from the commutator by this method and the face of each segment will have a true curvature. This condition, as has been pointed out, is not always attained in turning; the cutting tool may twist the segments enough that one edge is cut slightly deeper than the other. Grinding, unlike turning, can often be done with the commutator running at full speed and any distortion due to this speed eliminated. If the full operating speed is too high for grinding with a stationary stone, it may be advantageous after grinding at a suitable surface speed to bring the commutator up to full speed and give it a final polish with a hand stone.

Turning is possibly the best method for shaping up a newly built commutator. It is more rapid than grinding for truing a commutator that is in bad condition. If the commutator has been well tightened and a very light final cut is taken the inequality of depth at opposite edges of the segments will be slight and may be removed by a final surfacing with a hand stone or a stone mounted in the tool post.

After a commutator has been finished by any of the foregoing methods, it should be thoroughly cleaned, the armature carefully blown out to remove all copper chips and dust that

may have lodged in the windings, the surface closely inspected and any copper that may have bridged across the mica removed. It should then be given a high potential test, 1,000 to 2,000 volts, to make sure that there are no grounds. These precautions will be found well worth the time they require in the subsequent troubles thereby avoided.

Burnishing.—Examination of a newly stoned or sand-papered commutator under a strong microscope will disclose numerous grooves and scratches. These can be removed and the final polish greatly improved by *burnishing the commutator with hard wood blocks*.

Hard maple is an excellent wood for this purpose and should be applied with the end grain against the commutator. There are various methods of application. A single block may be held against the commutator by hand, in the same manner that a hand stone is applied. Another method frequently used is to replace the brushes with hard wood blocks cut to brush size.

In the case of a motor which cannot conveniently be driven from a separate source of power, enough brushes can be left on the commutator to drive the motor at normal speed. Enough blocks should be used and their position so arranged that all of the commutator surface on which brushes are to bear will be contacted by the burnishing blocks. A method often used in the factory, and likewise applicable in the repair shop, is to surround the commutator with a metal band lined with hard wood blocks and applied in the same manner as a *Prony brake*.

For effective burnishing action the blocks should be applied with considerable pressure. Since their friction is high, this generates a great deal of heat and care should be taken not to raise the commutator temperature to a point which causes

excessive expansion of the segments and distortion along their length.

In addition to removing all rough edges from the commutator surface, burnishing serves another useful purpose. The temperature developed in the course of this operation forms a thin oxide film on the commutator which has a favorable influence on brush performance.

Undercutting Mica of Commutators

Object of Undercutting Mica.—The object of undercutting the mica of commutators is to remove the mica between the copper segments so that the segments will wear evenly.

The removal of all the mica between the segments is imperative. Mica is built up of flakes of thin layers, and if the thinnest fin or section is left along the side of the slot, the brushes will be raised off the commutator, causing poor commutation, distinguishable by spitting and burning, exactly as though there were no undercutting at all.

Tools for Undercutting Mica.—Many tools are now on the market, some hand operated and some motor driven, by means of which commutators can be undercut in a workmanlike manner and at reasonable cost. Electrical manufacturers and large shops often have efficient tools for this purpose, designed and built in their own shops. An effective hand tool is the slotting file, illustrated in fig. 14. This type of tool cuts a V-shaped slot and can be obtained with either a 40° or 60° angle between the cutting edges. It is an excellent tool for undercutting commutators of moderate size as well as for beveling the edges of square bottom or U-shaped slots.

A piece of hacksaw blade, mounted in a suitable holder, is often used for undercutting where the amount of work to be

done does not justify the purchase of special equipment. Such a tool is satisfactory providing a sharp blade which cuts the mica freely is always used. If the blade is allowed to become dull it tends to drag the mica from the slot and may be open to the same objection as the hook-shaped scraper previously mentioned.



FIG. 14.—Showing slotting file for undercutting mica on commutator.

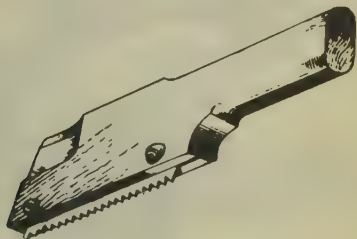


FIG. 15.—Showing method of mounting hacksaw blade in holder for undercutting of commutator mica.

A motor driven undercutter of the reciprocating type is shown in fig. 16. This type tool is easy to guide, cuts rapidly, and permits cutting clear up to the commutator risers. It is suitable for use on commutators of almost any size and has the advantage of requiring little clearance between the brush arms. The cutting blade is a V-shaped file.

When a large amount of undercutting is to be done, the motor driven, rotary type cutter undoubtedly has preference because of its speed and the quality of work performed. There are many types of machines of this general class on the market. Some are designed for mounting on a lathe or other machine tool. Others are complete shop units, capable of holding an armature on centers, or other type of support, while the commutator is being undercut.



FIG. 16.—The reciprocating type undercutter shown requires little clearance between brush arms and cuts close to the commutator risers. As a general rule, the best results will be obtained by supporting most of the weight in the hands so that the file touches the commutator lightly and the motor operates at nearly full speed.

Still others are portable, designed for use without removing the armature from its bearings, although some types require the removal of one or more brush arms. In some types the small driving motor is an integral part of the unit, while in other types, the motor is connected to the saw or cutter through the medium of a flexible shaft.

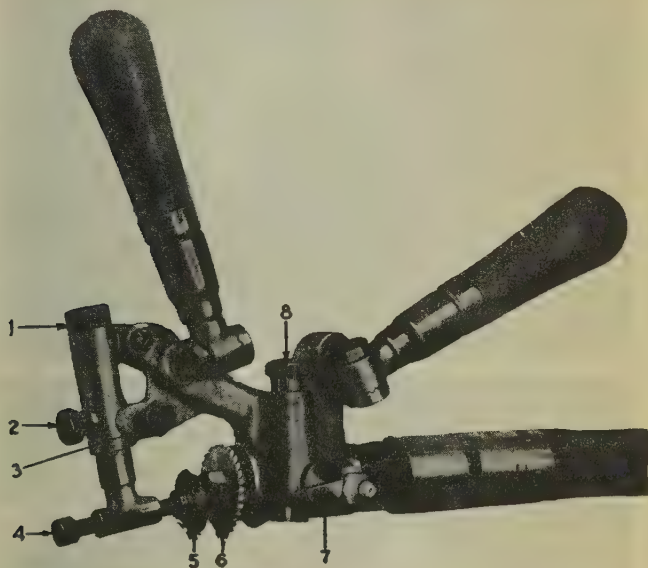
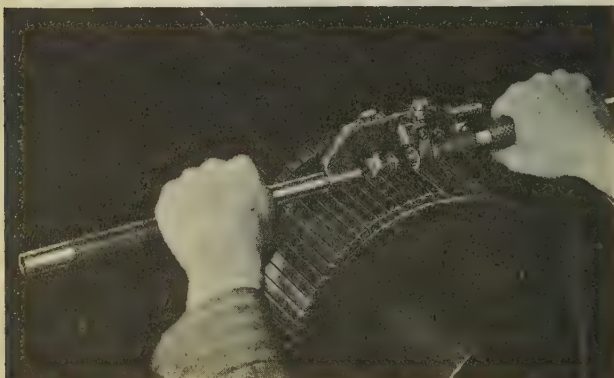
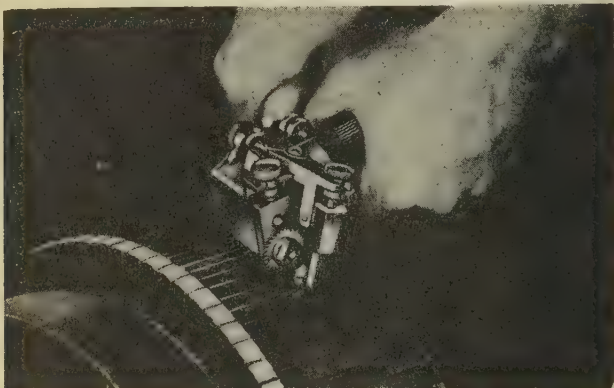


FIG. 17.—Typical rotary mica undercutter. Rotary type mica undercutters are generally preferred for their speed and the quality of work performed.

Each type of undercutting tool has certain advantageous features. The type shown in fig. 17 illustrates several features that are desirable in undercutting equipment. Adjustable handles can be adapted to the convenience of the operator.

Either a V-shaped or a U-shaped cutter (6) can be used. The slot guide wheel (5) has three adjustments, one for vertical position (1, 2), one for commutator curvature (3) and one for bar width (4). A depth gauge (7, 8) maintains uniform depth of slot. A similar machine, with the axis of the flexible shaft at right angles to the cutter axis, is adapted to use where there



FIGS. 18 and 19.—Showing undercutting of commutator mica with rotary type tools.

is limited clearance between brush arms. Standard cutters are available from .015 in. to .045 in. in thickness.

Before beginning the work of undercutting, the commutator surface should be turned, ground or stoned, as its previous condition may dictate. All grooves, ridges, eccentricity, flat spots, and other surface faults should be eliminated and except for final polish, a true cylindrical surface established. *No lubricant of any kind should be used in undercutting and lubricant should not be applied to a commutator that has been undercut.* The presence of oil or grease may result in an accumulation of carbon or copper dust in the slots, causing short circuits and damage to the armature coils.

For a similar reason, artificially lubricated brushes from which any oil or wax may be driven in the course of operation should not be used on a slotted commutator. Where oil may creep in from the bearings or where the machine operates in a moist, oily or dirty location, it is often advantageous, after slotting, to coat the slots with a good air-drying, insulating varnish. After this is thoroughly dry, it should be removed from the outer surface of the commutator with sandpaper or a commutator stone.

Form of Slots.—The question of preferable slot form has led to a great deal of discussion. The square bottom or U-shaped slot, fig. 20, has the advantage, when the work is carefully done, of being effective until the commutator has worn down the full depth of the undercut. Since non-abrasive brushes are now used on most undercut commutators, the need for frequent re-slotting is avoided. However, accumulated dust is not thrown out from the U-shaped slot by the action of centrifugal force as readily as it is from the V-shaped slot. It is best not to cut U-shaped slots deeper than $\frac{1}{32}$ inch, or at most $\frac{3}{64}$ inch for mica of average thickness.

When cutting U-shaped slots with a rotary cutter it is impossible to prevent the cutter from coming in contact with the sides of the bars, and wherever this occurs, some of the copper is cut or dragged off. Sometimes the dragging or tearing action is pronounced. This leaves jagged edges on the commutator segments and also has the effect of cold-drawing on the side of the bar, which causes a hardening of the copper at that point.

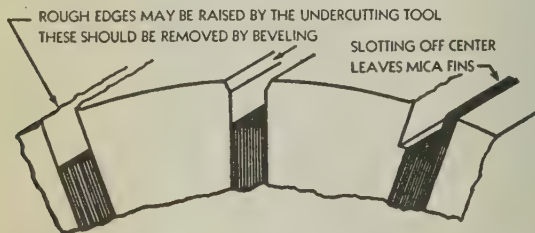


FIG. 20.—Showing U-shaped commutator slots. The depth of U-shaped slots should not appreciably exceed the thickness of the mica. Bar edges should be beveled and all mica fins removed. This beveling accomplishes two things; it removes the burrs caused by the stone dragging copper over the slots, and eliminates the sharp edge at the entering side of the bar under a brush. The bevel on the bars is done with a special beveling tool and should be about $\frac{1}{32}$ chamfer at 45 degrees, for medium thickness of bars. For thinner or wider bars, the beveling can be changed accordingly.

No matter how carefully the surface of the commutator may be smoothed or polished after slotting, there is a knife edge of hardened copper at the edges of each bar. This hardened edge will not wear down uniformly with the softer center of the bar and after a time will have a tendency to cause the bar edges to act as scrapers against the brush face. It is, therefore, advisable always to bevel the edge of the commutator bars as indicated in fig. 20. A beveled face of about $\frac{1}{32}$ inch is usually sufficient to remove any roughness or edge hardening that

might be disturbing to the brush faces. A slotting file, like that shown in fig. 14 or a suitable shaped scraper is an effective tool for this purpose.

It is also highly important to see that no fins of mica are left along the sides of the slots. Often the undercutting tool does not follow the line of the mica perfectly, leaving thin edges of uncut mica in the slots. This faulty condition is sometimes described as *feather-edge mica*. These mica fins may prove almost as troublesome as an unslotted commutator. After undercutting, every slot should be closely inspected and all mica fins removed with a knife blade or other suitable tool.

V-shaped slots are usually cut either with a slotting file or with a V-tooth rotary cutter. The latter are available with a 40°, 50° or 60° angle between the cutting edges. 40° cutters are generally preferred for thin mica; 50° for medium mica and 60° for thick mica. A cut $\frac{1}{16}$ inch deep and accurately centered on the mica will leave $\frac{1}{32}$ inch free copper above the mica if a 40° cutter is used on .023 inch mica; a 50° cutter on .029 inch mica or a 60° cutter on .036 inch mica.

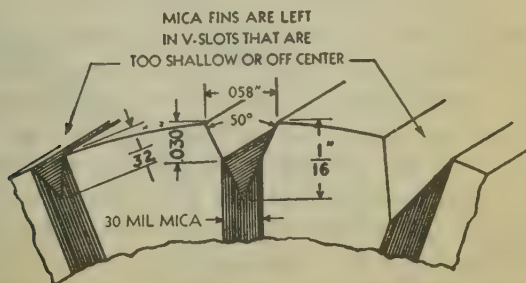
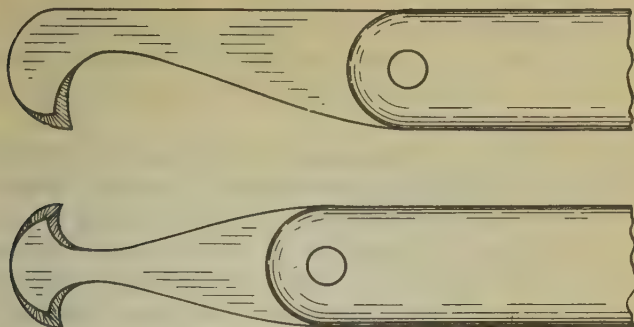


FIG. 21.—Showing V-shaped commutator slots. This type of commutator slot has the advantage over the U-shaped slot in that it keeps free of deposits at low commutator surface speeds. It also obviates the necessity for beveling; it requires, however, very accurate centering and workmanship.

It is very important when cutting V-shaped slots to keep the cutter accurately centered on the mica. In the typical example illustrated in fig. 21 a departure of less than $\frac{1}{64}$ inch from the center line of the mica would allow a mica fin to reach the commutator surface. Mica fins in V slots, being wedge shaped, are more difficult to remove than the fins of uniform thickness left at the sides of U-shaped slots by inaccurate centering of the cutter. However, the fact that V-shaped slots keep free from deposit at very low speed and do not require a separate operation for beveling of the bar edges, causes this form of slot to be preferred by many operators.

Mica Fins.—A frequent source of trouble on undercut commutators is variously described as *feather-edge mica*, *side mica* or *mica fins*. These terms refer to the thin edges of mica often left along the sides of the slots through failure to center the cutter accurately on the mica, deviation from a straight line parallel to the commutator segments, or insufficient depth of V-shaped slots. Commutator wear may also reach mica fins not in evidence immediately after undercutting.

Troubles traceable to feather-edge mica are encountered with such frequency on commutating equipment, and the cause is so often overlooked in the search for less tangible faults, that the avoidance of this condition justifies special care. It results in difficulties of the same type as those encountered on non-undercut commutators when the mica becomes "high". In fact it may be even more troublesome than ordinary high mica due to the tendency for small particles of mica to break loose and become embedded in the brush faces. Sparking, bar burning, picking up of copper by the brush faces and noisy operation are among the operating difficulties often traced to this fault.



FIGS. 22 and 23.—Typical hand tools for removal of mica fins.

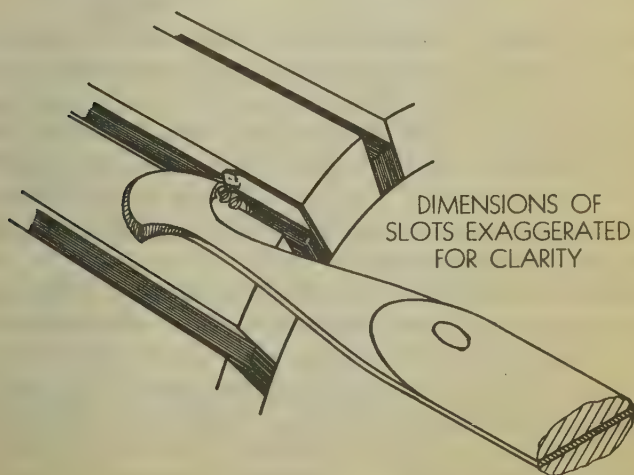


FIG. 24.—Illustrating removal of mica fins and chamfering edge of commutator bar with home made tool.

After undercutting the commutator or whenever faulty operation indicates the possible presence of feather-edge mica, every slot on the commutator should be inspected carefully. If mica fins are detected, they should be removed with a knife blade or other suitable tool.

An effective tool for this purpose can be made by grinding a hook-shaped cutting edge at the end of a hacksaw blade and attaching a suitable handle. This type of tool can be drawn through the slot, as illustrated in fig. 24, cutting at the root of the side mica on one side and slightly chamfering the opposite edge of the slot at the same time. Of course frequent re-sharpening will be necessary to insure complete removal of the mica. After completing this operation the slots and armature windings should be blown out thoroughly to remove all loose particles of mica and copper.

Canvas Wiper.—Another home made device which has proved effective in maintaining good brush performance, is the canvas wiper, fig. 25. Several layers of six- or eight-ounce hard-woven canvas or duck are folded over the end of a strip of strong pliable wood of suitable dimensions and secured by rivets. Counter-sinking the strip at the points where the rivets are inserted reduces the danger of the rivet heads making contact with the commutator.

The canvas is held against the commutator under heavy pressure and rubbed slowly back and forth. This removes oil, grease and smudge from the commutator surface without hazard of the hand coming in contact with live parts of the machine. Applied with sufficient frequency, it removes the oxidation at bar edges caused by sparking and may forestall the development of serious bar burning. However, it does not destroy the desirable oxide or electrographitic surface film on which good brush performance is largely dependent. Maintenance depart-

ments which have adopted the use of the canvas wiper as regular practice have found commutator maintenance greatly reduced.

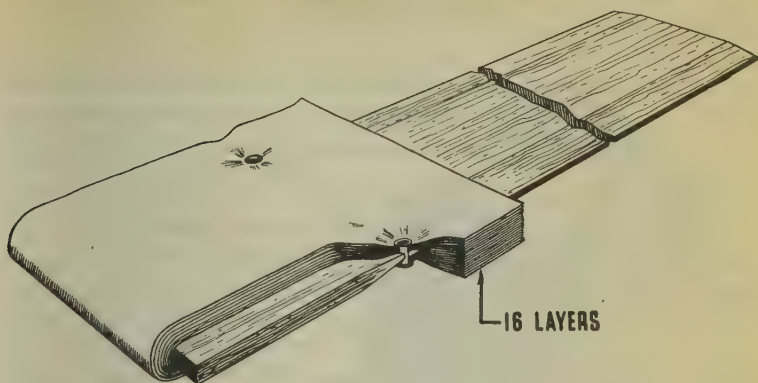


FIG. 25.—Illustrating construction method of simple but effective canvas wiper.

This has proved a very effective method of establishing and maintaining a good commutator surface with a minimum of major resurfacing operations.

Frequency of application depends on the tendency for surface deposit to accumulate. With moderate accumulation, daily application is recommended while more severe conditions may require application at shorter intervals.

Appearance of Good Commutator.—A commutator in good condition should be clean, true and smooth and have a medium polish.

The surface should have stable, copper-oxide-carbon color film (not a bright copper surface) and the mica should be undercut.

The commutator should be kept clean and well polished. If necessary the commutator should be cleaned occasionally with a pad of canvas or other similar hard-woven non-linting material. *Under no conditions should grease or other lubricant be used on the commutator.*



FIG. 26.—Method of application of canvas wiper to commutator. Holding the strip at right angles to the machine shaft is usually the most convenient method of application on small machines. (Courtesy National Carbon Company, Inc.)

BRUSHES

Functions of Brushes.—Successful operation of electrical equipment depends largely upon the selection of the brushes most suitable for the service requirements.

They have three distinct functions to perform, namely:

1. They must carry the load current into and away from the rotating element of the machine.
2. They must function as bearings on the surface of the commutator or slip ring without any applied lubrication, and at surface speed sometimes in excess of 8,000 ft. per minute.
3. On commutating machines, the brushes must control within safe limits the short circuit current resulting from uncompensated voltages in the armature coils undergoing commutation and must resist the destructive action of the very high local current densities which are frequently characteristic of the commutation cycle.

In addition to the need for good electrical conductivity, heavy demands are placed on the lubricating, thermal and refractory properties of the brush material.

Kinds of Brushes.—Various kinds of brushes are available suitable for different applications and atmospheric conditions. Graphite brushes, however, are most widely used because of their lubricating qualities. It is very important irrespective of what type of brushes are used, that the brushes have sufficient cross-sectional area and be of a sufficient number to carry the maximum current of the machine without undue heating.

Current Density.—The current carrying capacity of brushes is usually expressed in amperes per square inch of the useful brush area in normal contact with the commutator surface. The current density varies for different brushes and applications, the highest being 150 *amp.* per sq. in. for certain metal graphite grades and the lowest 30 *amp.* per sq. in. for certain super-baked grades.

The characteristics of various grades of brushes for different types of service are given in Table 1.

Brush Holders.—There are numerous styles of brush holders in use. The function of each, however, is to hold the brush at the correct angle and to maintain the necessary brush pressure on the commutator.

The brush holders are usually clamped to a stud which in turn is bolted to a rocker, which holds the studs equally spaced around the commutator. The rocker is clamped around the bearing housing inside the front bracket.

Most brush holder designs fall into three general classes, namely:

1. Reaction type.
2. Box type.
5. Clamp type.

Reaction type holders are so mounted as to hold the brush at a considerable inclination from the radial, firm contact with the flat plate of the holder being maintained by the reaction on the brush between the pressure arm and the commutator.

It is customary to bevel the holder end as well as the face of brushes used in reaction type holders. The brush is usually inclined 30° or more from the radial and operated in the leading position to avoid the wedging action and higher friction associated with trailing operation. The holder illustrated in fig. 30

TABLE I. SUMMARY OF TYPICAL BRUSH CHARACTERISTICS
(Courtesy National Carbon Company, Inc.)

Grade No.	Composition	Resistance, ohms per inch cube	Transverse strength, lb/sq in.	Hardness, scleroscope	Carrying capacity in amp/sq continuous service on commutating machines	Maximum peripheral speed, ft per min	Contact drop*		Coefficient of friction
							Relative position	Class	
234	Electrographitic grades	0.0020	2960	52	60	6,000	22	VH	Low
255		0.0018	3000	63	55	5,500	19	H	Low
258		0.00072	5100	42	60	5,500	20	H	Low
259		0.0020	2900	53	60	6,000	21	VH	Low
AY		0.0004	3850	31	60	4,000	18	M	Medium
E	Graphite-carbon grades	0.0014	4800	60	35	4,000	15	M	Medium
840		0.0011	3500	37	45	4,000	8	L	High
869		0.0013	3500	45	45	3,500	12	L	Medium
M-3		0.0012	4500	45	45	4,500	10	M	Medium
401	Super-baked grades	0.0016	5000	74	40	3,500	16	M	Medium
402		0.0013	5500	65	45	4,000	17	M	Medium
405		0.0022	5600	82	30	4,000	14	M	High
414		0.0004	4000	27	55	3,800	23	VH	Medium
441		0.0017	6000	85	40	3,500	13	M	Medium
543	Metal-graphite grades	0.000003	9700	4	150	4,000	1	VL	Medium
549		0.00025	4200	21	85	4,500	7	L	Low
840K†		0.00015	6500	40	75	3,500	6	VL	Medium
AYK†		0.00012	6000	31	85	3,500	9	L	Medium
NJC		0.000012	8000	8	150	4,000	3	VL	Medium
NJ25		0.000020	4000	10	100	4,500	4	VL	Medium
ET-10		0.0000047	4900	19	115	6,000	2	VL	Low
619	Graphite grades	0.00055	2100	20	60	6,000	11	L	High
634		0.0010	1100	16	60	12,000	5	VL	Medium
HRG		0.0020	4800	8	50	6,500	24	VH	Low

* L = Low, H = High, VL = Very Low, VIL = Very High.

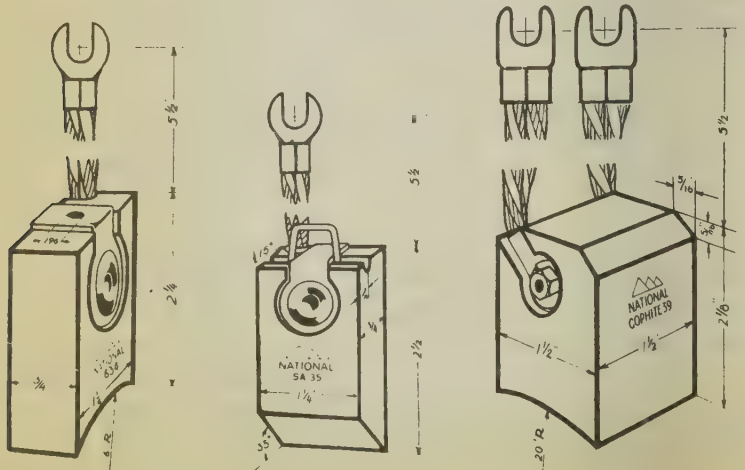
† Copper impregnated.

is representative of the reaction type. The use of shunts on brushes operated in reaction type holders is general practice.

Box type holders, as the name implies, provide a box-like support for the brush with sufficient depth to hold the brush in a stable position on the commutator. This type of holder is

made in a great variety of styles, one of which is shown in fig. 31. It can be adapted to any position of operation—leading, trailing or radial, and is probably the type in most general use.

When operated at sufficient inclination in the leading position, the action is essentially the same as that of a reaction type holder. At less inclination, when this reaction effect is not in evidence, it is desirable that the clearance between the brush and the holder box be as small as is consistent with freedom of motion. Brush thickness is normally held between limits of exact normal size and .004 in. under. Variation in the corresponding dimensions of the holder box should not exceed .003 in. to .004 in. with the minimum limit .002 in. over the nominal size. This allows a minimum clearance of .002 in. and a maximum of .009 in. to .010 in.



FIGS. 27 TO 29.—Showing various types of brushes and method used in attachment of shunt connections. (Courtesy National Carbon Company, Inc.)

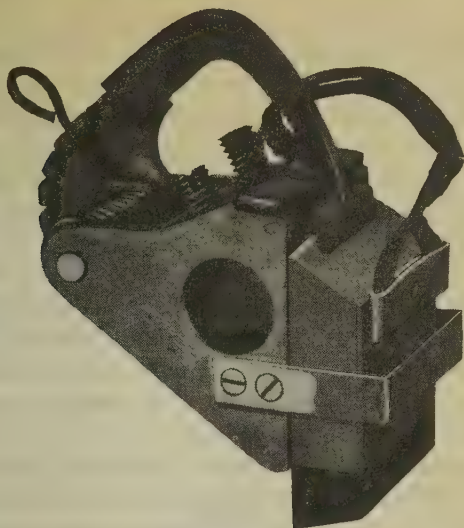


FIG. 30.—Reaction type brush holder.



FIG. 31.—Box type brush holder.

Excessive clearance between the brush and the holder box allows the brush to tip and disturb the contact with the commutator. This is especially true with reversing type series wound motors where the brushes are usually radial and there is no reaction effect to give stability to the brush position. Brush holder boxes should be inspected before new brushes are installed, and if badly worn, liners should be inserted to restore proper clearance.

On stationary machines with box type holders the brushes are usually equipped with shunts but on traction, crane and other series type motors the use of unshunted brushes is often encountered. Serious wear, known as *hammer-wear* or *side-wear* often results from the passage of current between the brush and the pressure arm or sides of the brush holder. While some of this wear is purely mechanical, the fact that it is greatly reduced by the use of brushes with shunts shows that much of it is traceable to poor electrical contact. The use of shunted brushes on equipment of this type is increasing.

In the clamp type holder, as illustrated in fig. 32, the brush is rigidly secured in the holder and the pressure spring acts through the clamping element of the holder to press the brush on the commutator. This type of holder is used on some small machines, where the combined mass of the brush and the moving element of the holder is small, but its use has largely been abandoned on larger machines and high speed commutators. This is because the inertia of the moving parts makes it difficult for the pressure spring to maintain intimate contact between brush and commutator.

Shunts are sometimes used on brushes in clamp type holders, but it is more general practice to use copper coated brushes without shunts.

Wherever shunted brushes are used, care should be taken before putting the machine in operation, to see that all shunt terminals are firmly secured at the point provided for their attachment.

It is desirable that clearance between the commutator and the nearest portion of the brush support in reaction and box type holders be kept small. From $\frac{1}{8}$ in. to $\frac{3}{16}$ in. clearance is sufficient for safe operation and close enough to give firm support to the brush except on small motors where less clearance is sometimes preferable.

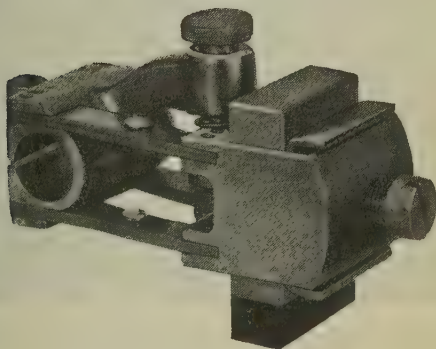


FIG. 32.—Clamp type brush holder.

It is also desirable that the angular position of all brush holders with respect to the commutator be uniform. These conditions should be established before the brushes are installed.

Brush Spacing.—Accurate spacing of the brushes around the commutator is a factor of major importance in obtaining satisfactory brush performance. If the spacing is not uniform, circulating currents flow between brush studs of like polarity due to their difference in potential on generators or the difference in counter *e.m.f.* on motors. These circulating currents may be high enough to cause serious heating of the armature windings and excessive current density in the brushes. Furthermore, it is impossible under such conditions to adjust all brushes to the best commutating position.

A convenient way to check the spacing after installing the brushes in the holders is to stretch a strip of paper entirely around the commutator underneath the brushes and mark it with a sharp pencil at the toe of each brush, identifying the marks in some manner with the several brush studs as indicated in fig. 33. If measurement shows these marks to be unevenly spaced, the brush holder supports should be adjusted to establish even spacing.

The method by which this is done will depend on the mechanical construction of the brush supporting elements of the machine. Even spacing of the brushes should not be accomplished by rocking the brush holders on the supporting studs as this is liable to leave some of the holders farther from the commutator surface than is desirable.

Many machines with *series* or *wave wound* armatures have only two brush arms. Obviously, multi-polar machines of this type are not susceptible to equalized brush spacing since the two brush arms are mounted one pole pitch apart. It is important, however, that the spacing from toe to toe of the brushes on these two studs be exactly one pole pitch. This can be accomplished by accurately measuring the circumference of the commutator dividing that measurement by the number of

poles and adjusting the distance between the brushes to the value so determined.



FIG. 33.—Showing method of checking brush spacing. To check the brush spacing accurately, place a strip of paper tightly around the commutator and mark it to the exact commutator circumference. Remove the paper, and accurately divide the circumference length into as many divisions as there are brush groups. Draw a line squarely across the paper at each division, to guide in locating the brushes. After the studs and brushes have been set accurately, it might seem reasonable to expect that if the brushes were put in the holders, they would be correctly spaced around the commutator. However, this may not be true; slight inaccuracies in the brush rigging may be accumulative, and cause an error in the brush spacing. Also, counting the number of commutator bars, and dividing them into as many equal groups as there are brush holder studs, cannot be used as a guide to check the brush spacing, because the commutator bars and the insulation between them may vary in thickness. (Courtesy General Electric Company.)

Alignment with Commutator Bars.—In addition to being evenly spaced around the commutator the edges of the brushes should be accurately aligned with the commutator segments. This can be determined by observation. If lack of alignment exists the cause should first be determined and correction made in the manner thereby indicated.

Some brush holders may have turned on the supporting stud, causing the brushes in those holders to bear on the commutator ahead of or behind their correct position. The brush stud or supporting arm may not be in line with the armature segments. Bending or shimming at the point of support may prove the best way to correct this condition.

Lack of alignment increases the overall span of the brushes on the arm at fault. It prolongs the commutation interval and may make it impossible to find a position at which the brushes will operate without sparking. Furthermore, the brush or brushes farthest out of line may be forced to take the brunt of commutation and be subject to destructive effects that would not occur were all brushes accurately placed.

A condition similar to that caused by inaccurate alignment of the brush holder studs is encountered if the commutator segments are skewed by careless assembly or by excessive tightening of the V-ring.

Unequal Air Gaps.—In checking over a machine preparatory to installing new brushes, or in an effort to locate the cause of unsatisfactory performance, it is important to check the air gap between the armature and pole faces. Should inequalities be found, either from pole to pole or under individual pole faces, the cause should be determined and all air gaps restored to equal value.

Unequal air gaps may be caused by a loose pole piece or pole face shoe, by improper alignment of the armature in the field

frame or by worn bearings. Commutation troubles, heating of the armature windings and loss of power often result from this condition.

The disturbing effects arising from inequalities of air gaps on multi-polar machines are due to the unbalancing of the magnetic circuit through the armature and field frame and the resulting unsymmetrical distribution of the field flux. These troubles are encountered in machines with lap wound armatures.

With this type of winding the span of the armature coils is limited to approximately one pole pitch, and the number of parallel current paths is equal to the number of poles. Under such conditions lack of magnetic symmetry produces inequalities of potential between brush arms of like polarity and causes circulating currents to flow through the brushes and the several armature paths. These currents may be very high even at no load and are augmented under load conditions by unequal distribution of the load current.

The series or wave winding has but two parallel paths and each coil extends around the entire circumference of the armature passing under each pole face. Even though the voltage generated under successive poles may differ, the sum of these voltages is the same in both armature paths and consequently there is essentially no tendency for unequal distribution of armature current with this type of winding.

It is a fortunate circumstance that the circulating currents which result from unequal air gaps produce magnetic effects of such direction that they tend to restore the symmetry of the field flux. This effect, however, is only partial, and while it minimizes, it does not prevent the disturbance of performance arising from this faulty machine condition.

Equalizing connections in the armature winding provide low resistance paths which relieve the brushes of circulating cur-

rents and tend to equalize distribution of current among the brushes of like polarity. They also tend to increase the demagnetizing effect on the field poles with short air gaps and strengthen those with longer air gaps. They do not entirely correct the magnetic distortion but machines with equalizing connections on the armature winding may reasonably be expected to give better performance under unsymmetrical field conditions than those which do not have this feature.

Spacing of Field Poles.—The necessity for equal spacing of brushes on the commutators of multiple circuit armatures has been discussed. It should be obvious that uniform spacing of field poles is of equal importance and for similar reasons. Lack of uniformity in pole spacing is a condition that is not frequently encountered, but it is sometimes found on frames with cast in pole pieces. If such a condition exists, it should be corrected by cutting off the tips of the pole face shoes on those poles which are less than the correct distance apart, care being taken to preserve uniform pole face span.

Staggering Brushes.—At one time practically all brushes, graphite as well as carbon, were decidedly abrasive and it was desirable where there was more than one brush per arm, to stagger the position of the holders so there were no strips of commutator surface not contacted by brushes. This was done to prevent the wearing of deep grooves in the commutator surface with sharp ridges between them.

Most brushes now used are non-abrasive or have very mild abrasive properties and deep grooving of the commutator surface is seldom encountered. However, the portion of the commutator on which brushes bear, looks different from that not touched by brushes and the practice of staggering brushes is continued for the sake of uniformity in commutator surface appearance.

The character of the surface film developed beneath the positive brushes is not the same as that under the negative brushes. For the sake of uniformity in appearance, as well as for certain advantages in respect to performance, the brushes should be staggered in positive and negative pairs, as illustrated in fig. 34. With this arrangement no part of the commutator surface is contacted by brushes of one polarity more than by those of the other.

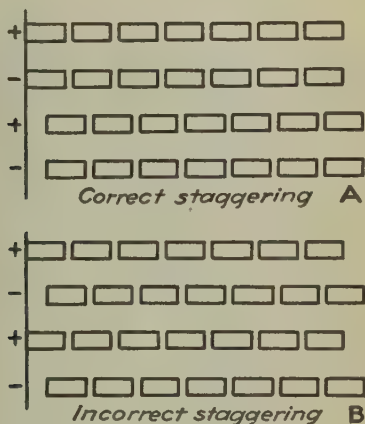


FIG. 34.—Showing *correct* and *incorrect* method of staggering brushes on commutator.

Seating Brushes.—The medium commonly used for seating brushes, that is, fitting the curvature of the brush face to that of the commutator is sandpaper. A coarse grade of sandpaper can be used for hard brushes until approximately full contact is obtained, but the final surface should be formed with sandpaper of fine grain.

Time may be saved by increasing the spring pressure on the brush while sanding or by pressing the brush down firmly by hand. Care must be taken, however, not to disturb the angle of the brush in the holder. It should have the same position in the holder during sanding that it will have in operation. Otherwise contact will be made only along one edge when the machine is put in service and injury to the commutator surface may result before the faces have worn in to full contact. It is important that the brush, in its normal running position, show a substantial area of contact from leading to trailing edge.

During the "roughing in" stages of sanding, the strip of sandpaper may be drawn back and forth under the brush face but it is preferable that the final surface be formed by drawing the sandpaper only toward that side of the brush holder against which the brush rests when in operation, lifting the brush to return the sandpaper strip for another cutting stroke.

Should the brush show signs of tipping under the high friction of the sandpaper, it should be held firmly against the side of the brush holder as the sandpaper is drawn through. Furthermore, the strip of sandpaper must be kept in contact with the commutator during the cutting stroke. Otherwise, it tends to round off the edge of the brush.

Metal graphite brushes are usually more difficult to sand in than carbon brushes but it is just as important that this operation be carefully performed. On large synchronous converters with several metal graphite brushes per ring, unequal distribution of current between the brushes on one ring is sometimes a source of operating difficulty. Imperfect contact at the brush face aggravates the tendency for unequal distribution to occur. It is, therefore, essential that brushes be as carefully seated on slip rings as on commutators.

Some machine manufacturers and operators prefer to use a brush seating stone rather than sandpaper for fitting brushes

to commutators or rings. The brush seating stone is a fine grain, free-wearing stone of special composition which can be purchased from various manufacturers of commutator maintenance equipment. It is held against the commutator or ring close to the brush as shown in fig. 35. Pressure on the brush should be increased during the seating operation. The fine particles worn away from the stone are carried under the brush face and grind it to the exact curvature of the commutator. Although this method of brush seating may effect the commutator surface film, it is claimed that no appreciable abrasion of the commutator results.



FIG. 35.—Showing method of applying brush seating stone.

A brush seating stone is somewhat easier to use than sandpaper and grinds the brush face to the exact contour of the commutator. Even though the thickness of the sandpaper is not great, it does give the brush face a slightly different radius

of curvature than the commutator surface, enough to leave a gap of several ten-thousandths of an inch at one or both edges of the brush when resting on the commutator. This slight gap may be sufficient to unfavorably affect the performance of the brush until it wears in to full span of contact.

Brush Pressure.—The spring pressure applied to brushes has a marked influence on brush performance. After a new set of brushes has been installed and seated to the commutator the spring tension on all brush holders should be adjusted to conform as closely as possible to the value recommended by the manufacturer for the grade installed.

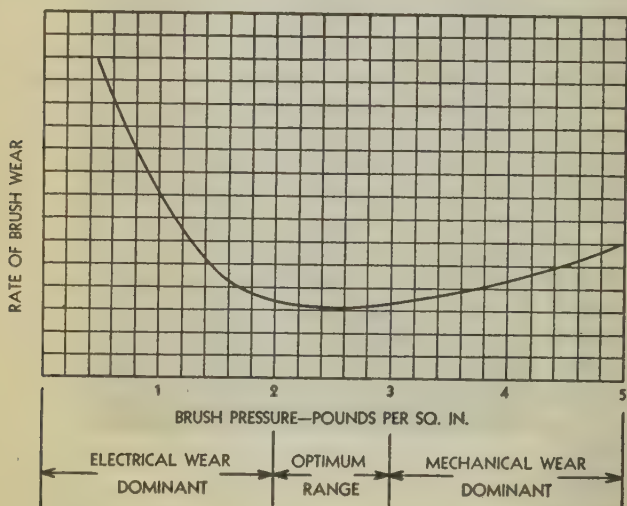


FIG. 36.—Curve showing relationship of pressure to brush wear of typical lampblack electro-graphitic grade. It will be observed that at a brush pressure in excess of three pounds per square inch mechanical wear predominates, whereas at very light brush pressure electrical wear is dominant.

There is a natural tendency on the part of operators to keep the spring tension low in order to reduce friction, losses and brush wear, but the resulting effect may be exactly opposite that intended. Brush pressure should be checked from time to time and adjusted to compensate for loss of tension due to wear of the brushes. Equal distribution of current among all the brushes on a machine requires that the pressure on all brushes be kept as nearly equal as the adjustment provided on the brush holders will permit.



FIG. 37.—Method of checking brush pressure by a spring scale. The brush pressure may be adjusted by means of the notches and spring lever that are provided on most brush holders.

A small spring scale provides a convenient means for measuring brush pressure. The reading of the scale should be observed just as the brush leaves the commutator. A good method is to slip a strip of paper under the brush face and pull on it gently while lifting with the spring scale against the tension of the brush holder pressure arm in a direction parallel to the sides of the brush holders. The scale should be read at the tension which just allows the paper to be pulled easily from under the brush.

Because of the more severe mechanical vibration encountered by the brushes on railway motors and series type motors in certain other fields of service, the brush pressures recommended are considerably higher than those for the same or corresponding grades in stationary service.

Brush pressures are recommended in terms of pounds per square inch. To determine the actual pressure which should be applied to a particular brush, multiply its cross sectional area in square inches by the recommended pressure. For industrial service, pressures of two to three pounds per square inch are generally recommended for electrographitic brushes, $1\frac{3}{4}$ to $2\frac{1}{2}$ pounds for carbon and carbon graphite grades, $1\frac{1}{4}$ to 2 pounds for the softer graphite brushes, but as much as 3 to 4 pounds for some firmly bonded graphite grades.

Recommendations for metal-graphite grades cover a considerable range depending on composition; $2\frac{1}{2}$ to $3\frac{1}{2}$ pounds per square inch are representative of the pressures recommended for metal-graphite slip ring brushes. Recommendations for traction service are usually on the order of 5 to 7 pounds per square inch.

Brush Position.—The best position for the brushes on a non-interpole machine depends on the design of the machine and also on the character of the load. Exact determination of the

mechanical or no load neutral point on non-interpole machines is of relatively small importance except in the case of series type motors which may be operated in either direction and are often operated as reversing motors. Such motors are usually built with the brush position fixed at the mechanical neutral which can be located by methods later discussed.

The mechanical or no load neutral is not the best position under load, since the field flux is distorted by the load current in the armature and best commutation is obtained with the brush position shifted against the direction of rotation. However, were the brushes fixed in the position of best commutation when the motor is operated in one direction, severe sparking would occur when the motor was reversed. The mechanical neutral is, therefore, selected as a compromise position best adapted to operation in either direction of rotation without brush shifting.

The brush rigging on industrial motors and generators is usually more accessible than on series type motors and they are accordingly designed to permit ready shifting of the brush positions. The point at which best commutation is obtained depends on the stiffness of the main field and the amount of load current.

On machines designed with a stiff field a brush position can often be selected which will give acceptable commutation over the entire load cycle. On more sensitive machines, however, it may be necessary to shift the brush position, from time to time, to compensate for changes in load. Brushes on *generators* should be shifted from the mechanical neutral in the *direction of armature rotation*, and on *motors*, *against the direction of rotation*.



FIG. 38.—To install brushes on D.C. machines, inspect the brush holders inside and out for burned spots that may have been caused by flashing at the commutators. If the inside of the holders shows roughness, remove this with fine sandpaper glued to a flat piece of wood. (Courtesy General Electric Company.)



FIG. 39.—Make sure the shunts are properly secured to the brushes and holders. If the connections of the shunts are defective, current will flow from the sides of the brushes into the holders and cause side burning, wear, overheating and improper brush operation. (Courtesy General Electric Company.)



FIG. 40.—When installing the brushes, make sure that they can move freely in the holders. They should not be so loose that there is any appreciable side play; on the other hand, they must not fit so tight that they may expand and stick at operating temperatures. (Courtesy General Electric Company.)

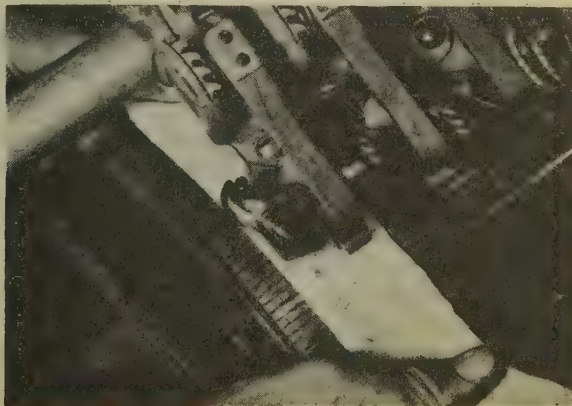


FIG. 41.—Fit the brushes to the commutator one at a time with a strip of sandpaper, first using a coarse grade and then a fine one, with the sand side turned to the brush face. Then, again thoroughly clean the brushes and holders, and adjust tension springs to about 2 pounds per square inch to hold the brushes on the commutator. (Courtesy General Electric Company.)

Location of No-Load Neutral

Importance of Correct Location.—Interpole machines have a *fixed neutral point* for all loads except very heavy overloads which produce saturation of the interpole core.

It is important from considerations other than commutation, that the brushes be located with exactness at this point. Several methods for locating the neutral point on interpole machines are in use. These may be grouped into three general classes, depending upon the particular methods used, as follows:

1. Voltage tests.
2. Speed tests.
3. Torque tests.

Prior to performing a test, however, it is important to see that brush spacing, pole spacing and air gaps have all been accurately equalized in order to insure symmetrical division of field flux. Correct polarity relationship of interpoles to main poles also be checked. Interpoles precede main field poles of like polarity on a generator and follow on a motor.

For the voltage tests it is advisable to use a multi-range voltmeter with scales for 15, 1.5 and 0.15 volts, or values of that order. Initial observations should be made on the high voltage scale, changing to the lower scales only after preliminary adjustments have brought the observed voltage within their range.

Minimum Short Circuit Voltage.—One of the most common voltage methods for locating the no load neutral is by finding the point of minimum drop in the short circuited coils. With the machine operating without load at full speed and voltage,

either as a motor or a generator, the terminals of the volt-meter leads are placed in contact with the commutator at the assumed location of the neutral point which should be approximately opposite the center of the main pole face.

These contact points should be a fixed distance apart, preferably one bar width or a distance corresponding to the brush thickness. They are moved back and forth until the position is found at which the volt-meter shows the lowest reading. Centering the brushes on this position, the test should be repeated and the point so found marked as the no load neutral of the machine. A further check, with the direction of rotation reversed, is sometimes of advantage.

Inductive Kick Method.—A more accurate method than the foregoing employs the inductive kick of the main field. When the main field circuit is closed or broken, voltage is induced in the armature windings. In armature conductors at equal distance to the right or left of the pole face center these voltages will be of equal magnitude but of opposite direction. Consequently, if the terminals of a low reading volt-meter are connected through the commutator to the armature conductors midway between pole faces, no voltage will be indicated when the field circuit is broken.

This test is applied with the armature at standstill. All of the brushes should be raised except one on each stud which has been beveled or shouldered at the face so as to make contact only on a narrow line at the center of the face and parallel to the commutator segments. Connect the leads of a multi-scale, low reading volt-meter to brush arms of opposite polarity.

Excite the main field winding with direct current from a separate source, preferably through a knife switch with a quick break blade in order to obtain the same inductive effect on each trial. Use only enough exciting current to get a good deflection on the volt-meter when the field circuit is broken.

Shift the brushes to different positions, taking the voltage reading at each position until the point of minimum reading is found. *This is the no load neutral.*

If the number of commutator segments is an integral multiple of the number of poles, there will be a range of one bar width within which the brushes serving as voltmeter terminals will remain on the same segments and no change in voltage readings will occur.

In such case, set two mica segments, one pole pitch apart, at the approximate neutral and take voltmeter readings between commutator bars adjacent to the selected mica segments, first on one side and then on the other. Rotate commutator slightly and repeat until a point is found where the readings to right and left of the mica are equal in value but opposite in polarity. The position of the mica will then mark the no load neutral and the center line of the brush faces should be set at that point.

Since the foregoing methods for locating the no load neutral do not involve the use of interpoles, they are applicable to non-interpole as well as interpole machines. These methods are also well adapted to use on large rotaries, generators and motors which cannot conveniently be reversed or mechanically driven from an external source of power.

Running Neutral Method.—Another voltage method, applicable only to interpole machines which can be mechanically driven at or near full speed, makes use of the interpoles themselves, and on this account, is preferred by many engineers. This method is based on the fact that, with a symmetrical interpole or commutating field and no main field, no terminal *e.m.f.* is generated when the brushes are in neutral position. When carefully used, this method is very accurate.

Remove all brushes except one on each arm, shouldered or beveled as described for the "kick" method, but with the contact face wide enough to bridge the mica and make contact with both adjacent commutator bars. Connect the shunt field through a reversing switch to a separate source of excitation and provide for separately exciting the interpole field winding. The series winding on the main field poles must carry no current. Drive the armature at normal speed in the direction of rotation it is intended to operate and demagnetize the main field poles by exciting the shunt field momentarily in the direction opposite to normal. Connect a low reading voltmeter to brush arms of opposite polarity and make sure that complete demagnetization has been effected so that no voltage is indicated with interpole field not excited. Excite the interpole field with 2 to 3% of normal current and adjust the brushes to a point where the lowest scale of the voltmeter shows no voltage.

Checks should be made at higher excitation and with direction of exciting current reversed, but it is not advisable to use an exciting current greater than 4 to 5% of normal. Check occasionally with no current in the interpole winding to make sure there is no residual magnetism in the main field.

On reversible motors it is well to make this test for both directions of rotation. The point so located should lie close together and the center line of the brushes should be set half way between them. This should also be done if the direction in which a non-reversing machine is to operate is unknown.

Speed Method.—A method frequently preferred for small interpole machines is based on the fact that when the brushes are at the neutral point the speed of rotation as a motor is the same in either direction. With field, voltage and load constant, the machine is run as a motor at full speed first in one direction and then in the other.

Speed is accurately measured in each direction and the brush position adjusted until the difference of speed in the two directions is a minimum. Should the best possible setting show a difference of more than 2% of rated speed, it is possible that the magnetic circuit of the machine is not symmetrical. This test may be made at any load, from no load to full load, provided the load is the same for both directions of rotation. The full load test is usually preferred.

Terminal Voltage Method.—For small generators the method just described is sometimes varied by driving the generator at exactly the same speed in each direction, with load and field the same, and adjusting the brush position so that the same terminal voltage is obtained.

Torque Method.—The torque test, also applicable only to small interpole machines, is made by operating the machine as a series motor, using only the armature and interpole field. Main field windings, both shunt and series are disconnected.

The main field should be demagnetized in the manner previously described, before making this test. The current applied through the armature and interpole field windings should be adjusted to about twice full load value. When the brushes have been set at the neutral point the torque applied to the armature will be neutralized and it will not rotate.

If there is an appreciable range of brush position within which no rotation of the armature occurs, the exact neutral can be located by turning the armature shaft by hand and locating the brush position at which the required turning effort is the same in either direction.

CHAPTER 15

Motor Installation and Maintenance

Location.—Where possible, install the motor in a place which is clean, dry, well ventilated, and where the motor will be accessible for inspection and care.

Foundation.—Rigidly support the motor, level it, and after accurate alignment with the driven unit, securely bolt in place.

Belt Drive.—Align the pulleys and see that the belt is just tight enough to carry the load without slipping. Belts of ample width obviate excessive tension. Run the smooth side of the belt next to the pulley. If possible, make the lower side of the belt the driving side. Vertical belt drives should be avoided. Locate the sliding base so that the adjusting screw comes on the side of the motor opposite the belt. Do not use double ply belts on pulleys smaller than 9 inches in diameter. The distance between the pulley centers should not be less than $2\frac{1}{2}$ times the diameter of the larger pulley. Where short center distances or vertical belt drives are absolutely necessary, a belt tightening attachment should be used.

Gear and Direct Connection.—Mount and fasten the units rigidly on a properly supported common base. Accurate alignment is essential. Where silent gear drive is especially desired confer with the motor manufacturer for recommendations.

Chain Drive.—Mount the motor so that the chain may be tightened. Secure accurate alignment. Avoid vertical drives if possible.

Safety Regulations.—All belts, chains, gears, couplings and machines should be properly housed or suitably guarded in accordance with the National, State or Local Safety Regulations in effect.

Floor, Wall or Ceiling Mounting.—All standard grease lubricated machines will usually operate successfully mounted on floor, wall or ceiling without changing the position of the end shield. Standard oil lubricated motors are assembled for floor installation unless otherwise desired. For wall or ceiling mounting, block armature, mark position of brushes on commutator, loosen yoke, rotate end shield so that the oil well cover will be horizontal in new operating position, see that the brushes have not moved from marked position on commutator, tighten yoke and unblock armature; in other words, maintain the same relative position between brushes and field coils.

Position of Terminal Plate.—It is standard practice to locate the terminal plate on the right hand side of the frame for motors when viewed from the commutator end.

Starting and Control Devices.—Instructions regarding proper installation, connections and operation should accompany each control device.

Protection.—Suitable thermal overload protection (if not incorporated in the control apparatus) should be installed to guard the motor against excessive overloads of long duration.

NOTE.—Whenever the end shields are removed, or rotated, make sure that the joints between end shields and stator frame are clean before the shields are replaced. Be sure that the grease in the V-grooves is renewed. The V-grooves are located at both ends of the bearing housings and are filled with a fibrous grease to keep out dust and dirt. Check the air gap and see that the armature revolves freely. Be sure to fill the oil wells after the motor is re-assembled.

External Wiring.—All motor and control wiring should be carefully installed in accordance with the National Electric Code and any local requirements, and should be of ample capacity based on a maximum drop of 2 per cent of line voltage at full load current.

OPERATION

Before Starting the Motor for the First Time.—1. Dry out all moisture. If the motor has been exposed to moist atmosphere for long periods while in transit or storage (or has remained idle for long periods after installing in moist atmosphere) it should always be dried out thoroughly before being placed in service. If possible, place the motor in an oven and bake at a temperature not exceeding 85°C . Fair results can be obtained by enclosing the motor with canvas or other covering, inserting some heating units or incandescent lamps to raise the temperature and leaving a hole at the top of the enclosure to permit the escape of moisture. The motor may also be dried out by passing a current at a low voltage (motor at rest) through the field windings that will raise the temperature to not over 85°C .

Increase the temperature gradually to this value, keeping the whole winding as nearly uniform in temperature as possible.

2. See that the voltage on motor and control name plates corresponds with the power supply.

3. Check all connections to the motor and control with the wiring diagrams.

4. Make sure that the drain plugs are tight and that the bearings are lubricated properly.

5. If oil ring bearings are used, make sure that the oil rings turn freely.

6. Remove all external load if possible and turn armature by hand to see that it rotates freely.

Before putting the motor in service, it is desirable to operate without load long enough to determine that there is no unusual localized heating.

Starting and Stopping.—The motor should come up to speed in about 5 to 20 seconds.

NOTE.—This does not apply to series motors. Series motors should not be operated without load.

MAINTENANCE

To insure the best operation make a systematic inspection at regular intervals, the frequency depending on service and operating conditions.

Cleanliness.—Keep both the interior and exterior of the motor and control free from dirt, water, oil and grease. Motors operating in dirty places should be periodically dis-assembled and thoroughly cleaned. Revarnishing the windings every year or two, depending upon operating conditions, will materially increase the life of the motor. A vacuum cleaner is highly recommended for cleaning assembled machines.

Brushes.—See that the brushes move freely in the holders and at the same time make firm, even contact with the commutator. The pressure should be between 2 and $2\frac{1}{2}$ lb. per square inch. Keep an extra set of brushes on hand. Fit the new brushes carefully to the commutator. The position of the brush yoke should not be changed on commutating pole motors.

Commutator.—Keep the commutator clean and maintain its polished surface. Ordinarily the commutator will require only occasional wiping with a piece of canvas or other non-linting substance. Do not use oil on commutator.

Heating.—The insulation of motors should successfully withstand a maximum observable temperature of 90° C. (194° F.). Hence do not depend on the hand to determine the temperature of a motor; use a thermometer.

Bearings.—The following instructions for oil ring bearings, ball or roller bearings, and waste-packed bearings should be applied to the particular type of bearing on the motor.

Ring Oiled Sleeve Bearings.—Fill the oil wells through the oil fillers with a good grade of light mineral oil of SAE viscosity No. 20 to within $\frac{1}{8}$ in. of the top of the oil filler gauge. Whenever the drainage plugs are removed, before replacing, clean and dip them in an oil sealing compound (such as G-E 1201 Red Glyptal); then replace and tighten securely to prevent oil leakage. Refill the oil wells at regular intervals, the frequency depending upon local conditions, such as cleanliness and severity or continuity of service.

GREASE LUBRICATED BALL BEARINGS

Greasing.—The bearing housings of grease lubricated ball bearing motors are usually packed with the proper amount of grease before leaving the manufacturer. The length of time before adding grease must be determined by the motor user since it depends upon the severity of operating conditions.

Ball bearing motors are usually equipped with pressure gun fittings and pressure relief plugs which, if used according to instructions, provide means for convenient addition of the proper amount of grease to the bearings.

As often as operating conditions demand, grease may be added to a bearing housing by means of a hand operated (as distinguished from pedal or air operated) pressure gun as follows:

1. Wipe clean the pressure gun fitting and the region around the fitting and relief plug.
2. Remove relief plug.
3. Free the relief hole of any hardened grease.
4. Add grease with the motor running until grease is expelled through the relief hole. Adding grease until new grease is expelled tends to purge the housing of used grease.
5. Run the motor a few minutes with the relief hole left open to allow excess grease to be expelled.
6. Clean and replace the relief plug.

NOTE.—Provided the bearing housings are kept tight so that the oil is retained and dirt and dust excluded, it will be found necessary to add lubricant only at long intervals.

Exclusion of dirt from the bearing housing and the lubricant is very important.

Only a high grade of grease, having the following general characteristics should be used for ball bearing lubrication:

1. Consistency a little stiffer than vaseline maintained with minimum change over the operating temperature range.
2. Melting point preferably above 150°C .
3. Freedom from separation of oil and soap under operating or storage conditions.
4. Freedom from abrasive matter, acid and alkali.

Cleaning.—Since the greasing method outlined has a tendency to purge the housing of used grease, complete removal of all grease should be required only at infrequent intervals. Whenever the motor is dis-assembled for general inspection and reconditioning, the bearings and bearing housings should be cleaned of old grease.

Bearing housings and bearings of horizontal motors operating at any angle not exceeding 15° from the horizontal may be cleaned without dis-assembly by flushing either with hot light mineral oil not hotter than 100°C . or with carbon tetrachloride. The latter is non-inflammable and dissolves grease more rapidly than hot oil. After flushing with carbon tetrachloride it is important that the housing be rinsed with light mineral oil to remove small amounts of carbon tetrachloride trapped in the bearing spacer and housing and to protect the clean bearing surfaces from atmospheric corrosion. Do not allow carbon tetrachloride to remain in contact with insulated windings in case of accidental splashing.

A bearing housing may be flushed as follows.

1. Remove pressure fitting and relief plug.
2. Free both holes of any hardened grease.
3. Pass flushing liquid through the bearing housing, with motor running until no grease comes out with the liquid.
4. Replace relief plug and continue cleaning by injecting and drawing off small amounts of liquid (by removing relief plug) until it draws out clear.

5. Replace relief plug and rinse housing free of carbon tetrachloride with small amounts of light mineral oil *if* carbon tetrachloride has been used for flushing.

6. Add grease according to instructions given under "*Greasing.*"

The lower bearing of vertical motors may be cleaned the same as a bearing in a horizontal motor; however, the upper bearing must be dis-assembled for cleaning and re-greasing.

WASTE PACKED BEARINGS

Waste packed bearings are shipped with a suitable packing already in place. This packing consists of a good grade of coarse wool yarn. Before putting the motor in service, remove the bottom drain plug and pour a liberal quantity of oil over the waste and lining, allowing the excess to drain away thoroughly before replacing the drain plug. Replace the drain plug, slushing it with a compound which will prevent oil leakage.

Bearings of open motors, which are supplied with overflow gauges, should be filled through the overflow gauge using sufficient oil to just fill the gauge. Bearings of enclosed motors, which have no overflow gauges, should be filled by pouring into the side of the bearing opposite the waste a quantity of oil corresponding to the following table:

SHAFT DIAM - INCHES	FLUID - OZ.
$\frac{3}{4}$	$\frac{3}{8}$
1	$\frac{5}{8}$
$1\frac{1}{8}$	$\frac{7}{8}$
$1\frac{1}{4}$	$1\frac{1}{4}$
$1\frac{3}{4}$	$1\frac{3}{4}$

NOTE.—The load on waste packed bearings should never come on the same side as the opening in the bearing lining.

Use a good grade of light mineral oil of SAE viscosity No. 20. Refill bearings at the end of the first month of operation under ordinary conditions of service and every three months thereafter, or as experience dictates. Remove the cover and drain plug in refilling, allowing the old oil to drain off. Pick up and re-pack the waste to prevent its becoming matted. At long intervals it may be necessary to remove the waste entirely and to clean the bearing thoroughly, inspecting it as to necessity for renewal, and to re-pack with clean waste.

TROUBLES

If trouble is experienced in the operation of a motor, make sure that:

1. The armature is free to revolve.
2. The bearings are in good condition and properly lubricated.
3. There is no mechanical obstruction to prevent rotation.
4. The air gap is substantially uniform.
5. All bolts and nuts are securely tightened.

In checking for electrical troubles, be sure :

1. That the voltage is actually available at the motor circuit switch and at the motor terminals.
2. That the voltage corresponds to the voltage stamped on the name plate of the motor.
3. That the fuses or other protective devices are in proper condition.
4. That all connections and contacts are properly made in the circuits between the control apparatus and the motor.

Checking these points first will frequently locate the cause of the trouble outside of the motor, where otherwise considerable time might be spent searching for it inside of the motor.

NOTE.—Sometimes the difficulty may be in the driven machine or load. It is desirable, therefore, to disconnect the motor from the load, if possible, and check the operation of the motor without load. If this is not possible and no definite trouble can be found in the motor, it is suggested that the driven machine or machines be carefully checked to see that the load on the motor is normal.

Belt and Pulleys

By definition a belt is *a continuous strip or band utilized for transmission of power from one pulley to another.*

The term *belting* generally is applied to all finished material from which a belt is made.

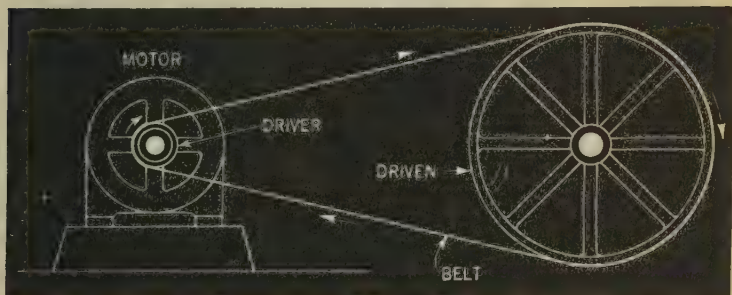


FIG. 1.—The *motor pulley* transmits the motivating force to the *driven pulley* by means of the connecting belt. As an easily remembered rule, therefore, the pulley which transmits or delivers the motion is termed the *driver* and the pulley which receives, or to which the motion is delivered, is termed the *driven*.

Materials.—The materials utilized in the manufacture of belting may be any one of the following: 1. *Leather*. 2. *Rubber*. 3. *Cotton*. 4. *Manila*. 5. *Hemp*. 6. *Steel*.

Belt Terms.—It is customary to name a belt from the manner of use to which it is put, as for example: **Cross belt**; **endless belts**; **wire belts**; **link belts**, etc.

Pulley Terms.—When power is transmitted from one pulley to another, the one which transmits the power is called the *driver* and the one which receives the power the *driven*.

Belt Drive Applications.—Where a speed change is desired in the transmission of power and where it is not absolutely essential to maintain a fixed ratio between the *driving* and *driven* shaft, belting is usually the best form of drive to use.

The tendency of slipping, especially under heavy overloads, is often beneficial in that it will absorb a portion of the shock of suddenly applied loads, and thus protect, to some extent, both the driving and driven machine.

Tanned or water proofed leather belts, fabric or rubber belts may be selected to meet practically any atmospheric condition.

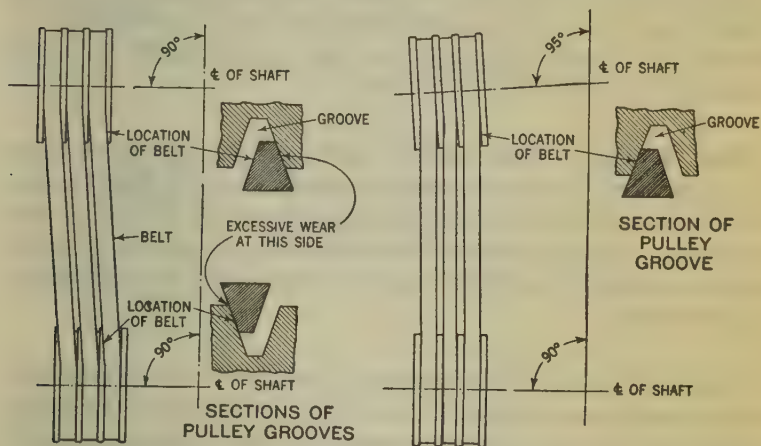
Leather Belts.—In the installation of leather belts, precautions should be taken to put the *flesh side* on the outside and the *grain* or *smooth* side toward the pulley. It has been found by experience that when the belt is installed in this manner it will wear much longer and deliver more power than if put on in the reverse way.

V-Belts.—A V-belt is an endless belt, with trapezoidal cross-section, running into a V-formed groove or grooves formed into the pulley surface.

The belts may be of either the single or multiple strand type, depending upon the amount of power to be transmitted. They are usually manufactured of rubberized cotton fabric and cord.

The advantage of this form of belting is that it may be used on short center drive with comparatively large pulley ratios. They are silent in operation, and have a very low slip factor. This with the addition of flexibility of operation range, offers a large field of usage.

Single Strand V-Belt Applications.—The single strand type is ideally suited for light intermittent drives, such as on small, air compressors, fan drives for automobiles, ventilators, etc.



FIGS. 2 and 3.—Showing necessity of correct pulley alignment when using V-belt drive. Fig. 2 shows two parallel shafts mis-aligned in a manner to cause excessive wear, tending to shorten the life of the belt. In fig. 3 the shafts are out of parallel with each other, tending to wear out the belt on the side indicated. The remedy in both cases is obvious.

Multiple Strand V-Belt Applications.—In larger transmissions of power the cross-sectional area of the belt is made up of several sections, according to requirements. The pulley sheave may be cut for a standard groove which allows the V-belt to sink into the groove so that the outside of the belt is flush with the outside diameter of the sheave, or the groove may be made in such a manner as to permit the belt to sink only partly into the groove as required.

Alignment.—The alignment procedure described previously should be adhered to, as it is particularly important that the shafting and pulleys be closely aligned when this type of drive is being used.

V-Belt Sheave Materials.—The sheave pulleys are generally manufactured of cast iron in which case the grooves are machined to give the required smoothness, although quite often die-pressed and welded sheaves are used—particularly in cases where lighter sheaves are required.

Cost of Belts.—The upkeep of belting is usually higher than for other forms of transmission, although this cost may be materially reduced if the proper quality of belt be employed and the belt be properly installed and cared for. The space requirement is somewhat greater than for other forms of mechanical transmission.

Speed of Belts.—The maximum speed of a belt should not exceed a mile per minute; if the speed be raised above this limit, insufficient contact friction between belt and pulley because of the effect of centrifugal force, tends to *throw* the belt.

The most economical speed has been found to be from 3,000 to 5,000 ft. per min. though practical limitations such as speed of shafting and pulley diameters, often limit belt speeds to much lower values.

How to Figure Belt Speed.—If for the sake of simplicity such factors as slip and creep be omitted, the belt speed will obviously be the same as that of the pulley surface on which it travels.

The circumferential speed (V) of the pulleys shown in fig. 4 may be written as:

$$V = \pi \times D \times N, \text{ ft. per min.} \dots \dots \dots (1)$$

Where V = speed in ft. per min.

D = pulley diameter in ft.

N = revolution per min. (*r.p.m.*) of pulley shaft

$\pi = 3.1416$

It will now be an easy matter to determine the speed of any belt, provided that the *r.p.m.* and the diameter of the pulley are known. The former may be determined by a reliable speed indicator, and the latter by direct measurement.

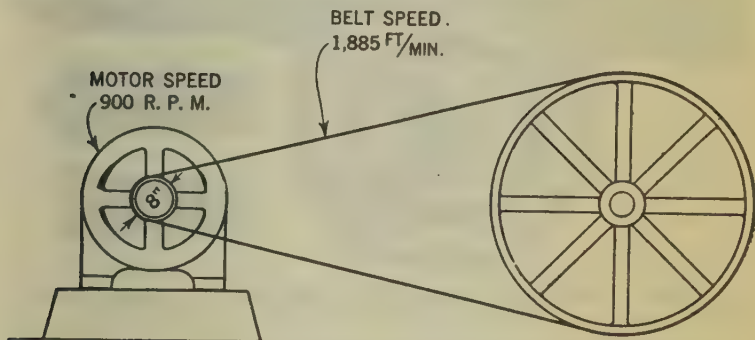


FIG. 4.—Illustrating relation between motor speed, motor pulley size and belt speed.

Example.—What is the belt speed when the full load speed of a motor is 900 *r.p.m.* and the diameter of the pulley 8 ins.?

Solution.—With reference to equation (1)

$$\text{The belt speed } V = \frac{\pi \times 8 \times 900}{12} = 1,885 \text{ ft. per min.}$$

Example.—Compute the belt speed of a motor having a full load speed of 860 *r.p.m.* when the diameter of the pulley is 10 ins.

Solution.—Inserting numerical values in the previously discussed equation then

$$V = \frac{\pi \times 860 \times 10}{12} = 2,255 \text{ ft. per min. approx.}$$

Speed Indicator.—With reference to fig. 5, the graduations show every revolution, and with two rows of figures read both right and left as the rotation of the shaft.

While looking at the watch, each hundred revolutions may be counted by allowing the oval headed pin on the revolving disc to pass under the thumb as the instrument is pressed to its shaft. A late improvement in this indicator consists in the rotating disc, which being carried by friction may be moved to the starting point where the raised knobs coincide.

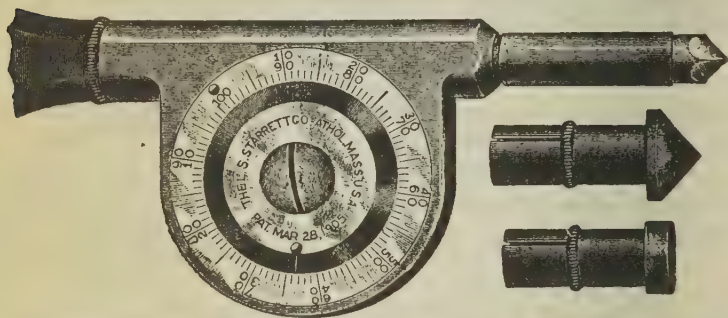


FIG. 5.—Starrett's improved speed indicator. The working parts are all enclosed similarly to that of a watch.

When the spindle is placed in connection with the revolving shaft, pressing the raised knob with the thumb will prevent the disc rotating, while the hands of the watch get to the right position to take the time.

By releasing the pressure the disc is liberated for counting the revolutions of the shaft when every 100 may be noted by feeling the knob pass under the thumb, lightly pressed against it, thus relieving the eye, which has only to look at the watch to note the time.

How to Figure Pulley Diameters.—There is no need to absorb a large quantity of formulae in order to determine pulley diameters and shaft speeds.

The only way to master anything completely is to understand how it works.

With reference to fig. 6 it is obvious that if such minor factors as that of slip and creep be omitted, the speed of the belt connecting the two pulleys is the same throughout the loop, i.e., any point on the driven pulley surface will travel at exactly the same speed as a corresponding point on the driver pulley surface, regardless of the difference in their respective diameters.

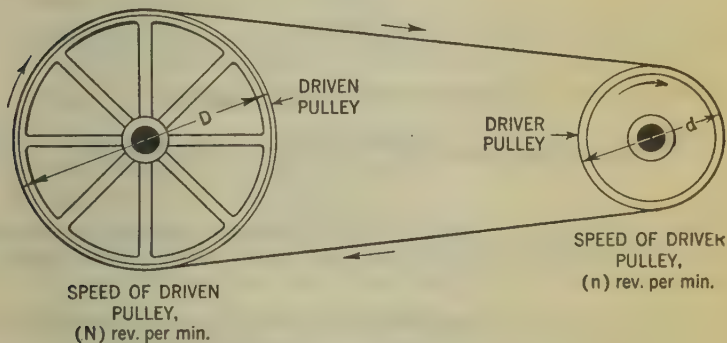


FIG. 6.—Showing relation between shaft and diameter of pulleys.

As the circumferential speeds (V) of the pulleys are equal, it may be written:

$$\pi \times D \times N = V = \pi \times d \times n, \text{ or } \dots \dots \dots (2)$$

$$D \times N = d \times n \dots \dots \dots (3)$$

Where D = diameter of *driven* pulley

d = diameter of *driver* pulley

N = revolutions per min. (*r.p.m.*) of *driven* pulley

n = revolutions per min. (*r.p.m.*) of *driver* pulley

From equation (3) the following formulae may be written

$$D = \frac{d \times n}{N} \dots\dots\dots (4)$$

$$d = \frac{D \times N}{n} \dots\dots\dots (5)$$

$$N = \frac{d \times n}{D} \dots\dots\dots (6)$$

$$n = \frac{D \times N}{d} \dots\dots\dots (7)$$

If the formulae be written down without abbreviations,

$$\text{Diam. of driven pulley} = \frac{\text{Diam. of driver pulley} \times \text{driver speed in } r.p.m.}{\text{Rev. per min. (} r.p.m.) \text{ of driven pulley}}$$

$$\text{Diam. of driver pulley} = \frac{\text{Diam. of driven pulley} \times r.p.m. \text{ of driven pulley}}{\text{Rev. per min. (} r.p.m.) \text{ of driver pulley}}$$

$$\text{Rev. per min. of driven pulley} = \frac{\text{Diam. of driver pulley} \times \text{driver speed in } r.p.m.}{\text{Diam. of driven pulley}}$$

$$\text{Rev. per min. of driver pulley} = \frac{\text{Diam. of driven pulley} \times \text{speed of driven pulley}}{\text{Diam. of driver pulley}}$$

In the above formulae the desired **driven** speed should be increased 2% to allow for belt slip.

To find diameter of driven pulley.

Example.—What size pulley is required on a 200 *r.p.m.* line shaft if it be driven by a 1200 *r.p.m.* motor having a pulley diameter of 4 inches?

Solution.—Substituting values in equation (4)

$$\text{Diam. of driven pulley } D = \frac{d \times n}{N} = \frac{4 \times 1200}{200} = 24 \text{ inches}$$

To find diameter of driver pulley.

Example.—What size pulley must be used on an 860 *r.p.m.* motor, employed to drive a fan at 215 *r.p.m.* when the fan pulley diameter is 24 inches?

Solution.—Substituting values in equation (5)

$$\text{Diam. of driver pulley, } d = \frac{D \times N}{n} = \frac{24 \times 215}{860} = 6 \text{ inches}$$

To find speed of driven pulley.

Example.—At what speed will a generator run if it has an 8 inch pulley and is driven by an engine having a 48 inch pulley and running at 180 *r.p.m.*

Solution.—Substituting values in equation (6)

$$\text{Rev. per min. of driven pulley, } N = \frac{d \times n}{D} = \frac{48 \times 180}{8} = 1,080 \text{ r.p.m.}$$

To find speed of driver pulley.

Example.—It is desired to run a line shaft at a speed of 170 *r.p.m.* by means of an induction motor. If the motor and line shaft pulley diameters be 12 and 60 inches respectively, what should be the speed of the motor?

Solution.—Substituting values in equation (7)

$$\text{Rev. per min. of driver pulley, } n = \frac{D \times N}{d} = \frac{60 \times 170}{12} = 850 \text{ r.p.m.}$$

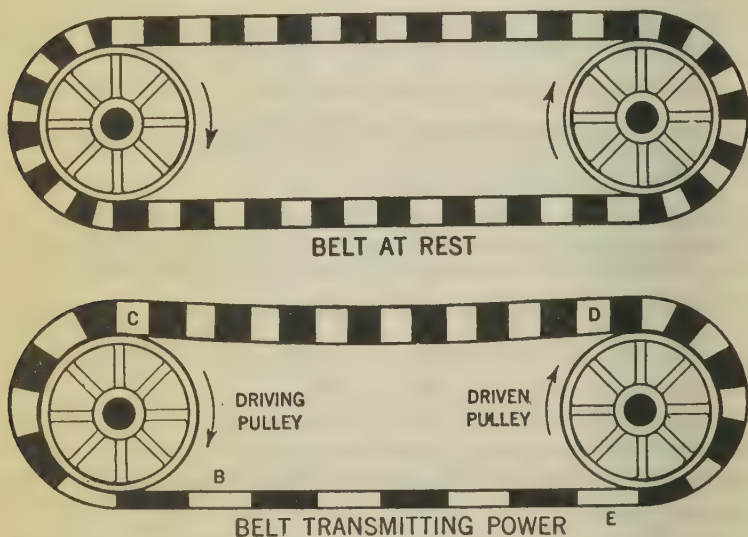
Creep in Belts.—It is a well known fact that slip causes a decrease in driven pulley speed below that which would be expected from the speed of the driver and the ratio of diameters of the two pulleys.

The result of *creep* similarly affects the speed of the driven pulley, and *slip* and *creep* jointly cause power loss.

The effect of slip may be greatly reduced by adhering to conservative pulley ratios and correct alignment, but creep, being a physical characteristic of the belt itself, is inherent in all power transmitting operations where belting is employed as the transmitting medium.

In order to obtain a clear conception regarding this phenomenon, the diagrams shown in figs. 7 and 8 will be of assistance.

Fig. 7 shows a belt drive in which the driving and driven pulleys are of equal diameters, and in order to facilitate the understanding of creep, the belt thickness has been greatly enlarged.



FIGS. 7 and 8.—Illustrating exaggerated belt thickness and condition of belt when at rest and when transmitting power. When pulleys are at rest the tension in the upper and lower strands is equal. When transmission of power takes place, the stretching and shortening of the upper and lower strands causes creep.

When the belt is first applied to the pulleys it must be given a certain initial tension, which is the same in both strands. It is this tension which causes friction between the belt and

pulley surfaces, and in this manner permits power to be transmitted from one pulley to the other.

When this transmission takes place the driving pulley rotates in the direction of arrow by action of its prime mover, and by so doing causes a pull on the lower strand of the belt.

Due to this increase in tension in the lower strands, there will be a decrease in tension in the upper strand. This causes the former to stretch and become thinner and the latter to contract and grow thicker as indicated.

As a result, a long section of belt **B**, at the driving pulley is delivered to **C**. This is due to the elasticity of the belting material. In a manner similar to that already described, a short section of belt **D**, is delivered to the pulley and it comes off a long section **E**.

The belt on the slack side in other words is being delivered to the pulley at a slower rate than it comes off on the tight side. The belt is therefore creeping ahead on the pulley and its belt surface runs slower than the belt itself.

Since the *creep* as already pointed out is caused by the elasticity of the belt, it increases with the load, and is usually somewhat less than one per cent at the load the belt is designed to carry under normal conditions. However, if the load on the belt be constantly increased above normal, a point will be reached where the friction between pulley and belt is not sufficient to drive the load, and the belt slips on either or both pulleys finally causing the belt to be thrown off.

Slip of Belts.—The effect of *creepage* and *slip* is to reduce the speed of the driven pulley and, consequently, the power transmitted. For commercial applications it will be close enough to multiply the calculated speed of the driven shaft by 98%, assuming 2% slip. The diameter of the driven pulley should be slightly smaller than that calculated on the basis of no slip, in

order to obtain a certain speed at the driven shaft. In other words, the speed of the driven shaft is reduced by slip unless compensated for by reducing the driven-pulley diameter a proportionate amount.

HOW TO FIGURE BELT SLIP

Example.—A synchronous motor having a full load speed of 900 *r.p.m.* and a pulley of 8 in. diameter, is required to drive a machine at a speed of 300 *r.p.m.* What should be the diameter of this pulley if the belt slip is estimated to be 2%?

Solution.—If *D* denotes the diameter of driven pulley; *d*, diameter of motor pulley; *n*, motor speed in *r.p.m.* and *N*, speed of driven pulley, then

$$D = \frac{d \times n}{N} = \frac{8 \times 900}{300} = 24 \text{ in.}$$

Finally, taking the belt slip into account it is evident that in order to compensate for this, the pulley should be slightly smaller which reduction is 24×0.98 or 23.52, say $23\frac{1}{2}$ ins.

A small amount of belt slip is not harmful, but excessive slip is. Severe slippage burns the belt, quickly destroying its usefulness, while at best, the belt surface is polished, so that the grip on the pulley is materially reduced. Belt slip can be detected by noting the condition of the pulley surface. When the belt is slipping, the pulley will have a very shiny appearance, as contrasted with the smooth, but rather dull appearance it should have.

What is the reason for excessive slip? Excessive slip is caused by poorly designed drives, where the driving pulley is too small or the load too great; by running the belt too loose; or by not giving proper attention to the care of the belt.

Balancing of Pulleys.—It is of the utmost importance especially in high speed drives that the pulleys be correctly balanced. This is necessary, because if the centrifugal forces generated by the pulleys rotation be greater at one side than at the other, it will cause the pulley shaft to vibrate whenever the amount of unbalanced centrifugal force becomes, on account of the speed of rotation, sufficient to bend the shaft or deflect the frames

holding the shaft. There are two methods of testing the balance of a pulley, namely:

1. The standing balance, and
2. The running balance.

A standing balance does not balance a pulley, but merely corrects the want of balance to a limited degree.

A running balance correctly balances a pulley when running up to a speed at which the balance was made, but does not balance for greater speed.

A standing balance is effected when the shaft being supported horizontally and with as little friction as possible, the pulley will remain at rest in any position in which it can be placed.

A common method of balancing is to set the pulley in slow rotation several times in succession, and if the same part of the pulley circumference comes to rest in each case at the bottom, then this particular part of the pulley is the heaviest and its weight should be reduced, or weight should be added to the diametrically opposite side.

How to Use Belt Speed Table.—In order to facilitate the calculation of belt speed in feet per minute, when the corresponding motor speed and pulley diameter is known, the table on the following page will be of assistance.

Example.—Assume the full load speed of a motor, having a pulley whose diameter is 11 inches, to be 1,750 *r.p.m.* what is the corresponding belt speed?

Solution.—On the 1,750 *r.p.m.* line in the table read the figure corresponding to a pulley diameter of 11 ins. which is 5,040. In other words, when an 11 inch diameter pulley rotates at 1,750 revolutions per minute, a belt on this pulley travels at a speed of 5,040 feet per minute. In a similar manner belt speed of motors whose *r.p.m.* and pulley diameters are given in the table may be read directly without calculation.

Table I—Belt Speeds

Full-Load Speed of Motor in Rpm	PULLEY DIAMETERS IN INCHES										
	3½	4	4½	5	5½	6	7	8	9	10	11
	Belt Speed in Feet per Minute										
1750	1605	1835	2060	2290	2520	2750	3205	3670	4125	4580	5040
1450	1330	1520	1710	1900	2090	2275	2660	3040	3420	3800	4170
1150	1055	1205	1355	1505	1655	1810	2110	2410	2710	3010	3315
860	790	900	1015	1130	1240	1350	1575	1800	2030	2255	2480
690	....	725	815	905	995	1085	1265	1445	1625	1810	1990
575	....	....	680	755	830	905	1055	1205	1355	1505	1655

Full-Load Speed of Motor in Rpm	PULLEY DIAMETERS IN INCHES										
	12	13	14	15	16	17	18	19	20	21	22
	Belt Speed in Feet per Minute										
1450	4560	4930									
1150	3615	3915	4220	4520	4820	5120					
860	2705	2930	3160	3380	3610	3835	4060	4280	4510	4740	4960
690	2170	2350	2530	2710	2890	3075	3250	3435	3615	3800	3980
575	1805	1955	2105	2260	2410	2560	2710	2860	3010	3160	3310

Full-Load Speed of Motor in Rpm	PULLEY DIAMETERS IN INCHES										
	23	24	25	26	27	28	29	30	31	32	33
	Belt Speed in Feet per Minute										
690	4160	4340	4520	4700	4880	5060					
575	3460	3610	3760	3915	4060	4210	4360	4515	4665	4815	4965

The above table is based on the formula:

$$\text{Belt speed in feet per minute} = \frac{3.1416 \times \text{pulley diameter in inches} \times \text{rpm}}{12}$$

(Table giving belt speed in ft. per min. corresponding to various motor speeds and pulley diameters.)

Length of Belts

The length of belts is found by various methods such as:

1. Direct measurement
2. Calculation
3. Scale

Direct Measurement.—This is the simplest and undoubtedly the safest method as well. A steel tape carefully adjusted over the pulley crowns will give the length of belting required. To this should be added a reasonable amount of material for jointing as required in each individual case.

Calculation.—The calculation method is useful in locations where a direct measurement cannot readily be obtained. In many instances it may be necessary to obtain the length of belting from *blue prints* where only shaft center distances and pulley diameters are given. This as a matter of fact, is most often the case especially on new constructions, where the entire plant machinery is laid out on drawings according to a *carefully engineered* plan.

In belting up such a plant it is imperative that the millwright has the knowledge necessary to intelligently cut and assemble belts without undue waste of material.

The author suggests that instead of copying or trying to learn formulae in *parrot fashion*, that an actual study of the elements involved be made and that the use of any formula should be made only after all the factors involved are clearly understood.

Generally, belts may be divided into two groups:

1. Belts driving their connecting pulleys in the *same* direction or **Open Belts**.
2. Belts driving their connecting pulleys in the *opposite* direction or **Crossed Belts**.

Formula for Length of Crossed Belts.—With reference to fig. 1 the exact length (L) of a crossed belt may be written

$$L = (\pi + \frac{\pi}{90} \times \phi) (R + r) + 2 \times C \cos \phi \dots \dots \dots (1)$$

Where R = radius of the larger pulley

r = radius of the smaller pulley

C = distance between shaft centers

ϕ = angle whose sine is $\frac{R+r}{C}$

Although this formula is found in most handbooks in one form or another, it should perhaps not be used unless the reader clearly understands its derivation.

The length of the belt with reference to the illustration is simply found by adding up the various elements involved. Thus, starting with the larger of the two pulleys, the length of pulley arc indicated by angle ϕ is

$\frac{2\pi R}{360} \times \phi$, but inasmuch as there are two such elements their combined lengths are $\frac{4\pi R}{360} \times \phi$.

In a similar manner the arcs on the smaller pulley are obtained as

$$\frac{4\pi r}{360} \times \phi.$$

To the four arcs should finally be added twice the distance EF, and half the circumference of each pulley.

The length (L) of the belt is hence

$$L = \frac{\pi R \phi}{90} + \frac{\pi r \phi}{90} + \pi R + \pi r + 2 C \cos \phi, \text{ which}$$

after re-arrangement of terms becomes

$$L = \left(\pi + \frac{\pi \phi}{90} \right) (R + r) + 2 C \cos \phi \text{ as previously written.}$$

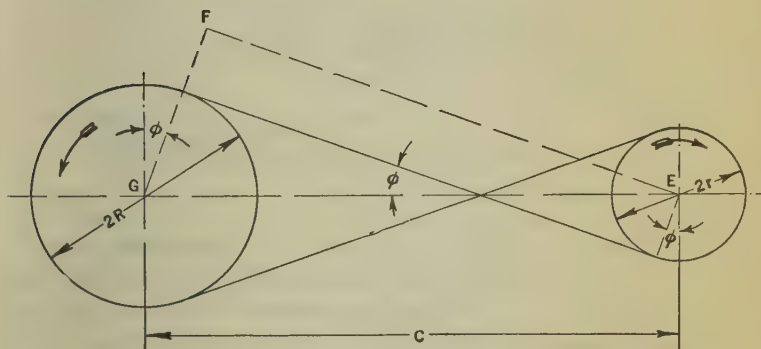


FIG. 1.—Diagram for calculation of length of a crossed belt.

If the radius of the pulleys be substituted for their diameters respectively the formula becomes

$$L = \left(\pi + \frac{\pi \phi}{90} \right) \left(\frac{D+d}{2} \right) + 2 C \cos \phi \dots \dots \dots (2)$$

A somewhat simpler formula giving the approximate length (L) of a crossed belt is—

$$L = \frac{\pi}{2} (D + d) + 2 \sqrt{C^2 + \left(\frac{D+d}{2} \right)^2} \dots \dots \dots (3)$$

Formula for Length of Open Belts.—Contrary to the case of a crossed belt, the exact length of an open belt is somewhat difficult to obtain; however, an approximate formula in which the errors do not exceed practical limitations is derived from fig. 2.

If the length between the pulley centers (C) be given, and the pulley diameter be respectively (D) and (d), then the length of the belt is—

$$L = \frac{\pi D}{2} + \frac{\pi d}{2} + 2\sqrt{C^2 + \left(\frac{D-d}{2}\right)^2} \quad \text{or}$$

$$L = \frac{\pi}{2}(D+d) + 2\sqrt{C^2 + \left(\frac{D-d}{2}\right)^2} \dots\dots\dots (4)$$

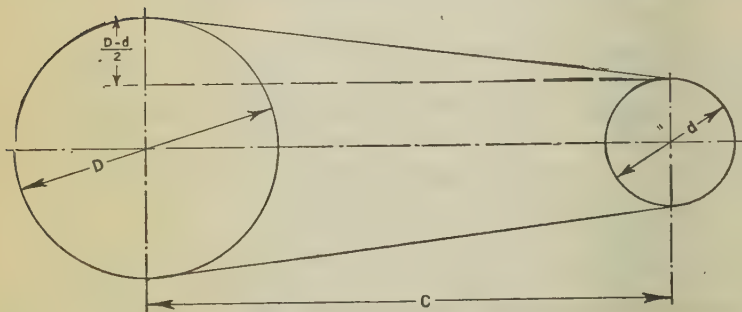


FIG. 2.—Diagram for calculation of length of an open belt.

Example.—The shaft center distance between two pulleys in an *open* belt drive is 12 ft. If the pulley diameters are 4 ft. and 1 ft. respectively what is the length of belting required?

Solution.—Substituting values in formula (4)

$$L = \frac{\pi}{2}(4+1) + 2\sqrt{12^2 + 1.5^2} \quad \text{or}$$

$$L = \frac{5\pi}{2} + 2\sqrt{146.25} = 7.854 + 2 \times 12.1 = 32.054 \text{ ft., say 32 ft.}$$

Example.—If in a *cross belt* transmission drive the pulley shaft distance be 10 ft. and the pulley diameters are 54 ins. and 9 ins. what length of belt should be used?

Solution.—Inserting values in formula (2) and remembering that the angle ϕ fig. 1 is that angle whose sine is $\frac{R+r}{C}$, then $\sin \phi = \frac{31.5}{120} = 0.2625$; from a table of natural sines and cosines the corresponding angle ϕ is 15.2 degrees.

Substituting numerical values,

$$L = \left(3.14 + 0.035 \times 15.2 \right) \left(\frac{4.50 + 0.75}{2} \right) + 2 \times 10 \times 0.9650$$

from which

$$L = 28.93 \text{ ft.}, \text{ say } 29 \text{ ft.}$$

Scale Method.—This method consists of laying out the pulley set at their proper distance apart, either full size or in a suitable scale and measure the length of the side of the belt, assuming the belt to envelop one half the circumference of each pulley, and to add to this, one half the circumference of each pulley.

Length of Belts for Equal Size Pulleys.—When the pulleys are of the same diameter, or nearly so, the length of an *open belt* may be obtained as follows:

Add together in inches the diameter of the two pulleys, then divide the result by 2; now, multiply the quotient by (π) or 3.14. Finally add in inches twice the distance between the pulley centers.

If this be written algebraically, we have

$$L = \frac{(D+d)\pi}{2} + 2C \dots\dots\dots (5)$$

where

L = Length of belt in inches

D = Diameter of the larger pulley in inches

d = Diameter of the smaller pulley in inches

C = Distance between pulley shaft centers in inches.

Example.—How many feet of belting is necessary to connect two pulleys of 28 and 21 inches diameter respectively, when their shaft center distance is 18 ft. 6 ins.?

Solution.—By employing the previously enumerated rule or formula,

$$L = \frac{(28+21)}{2} 3.14 + 2 \times 12 \times 18.5 = 520.93 \text{ inches}$$

If this be divided by 12 to obtain feet the result is 43.41 ft. or 43 ft. 5 ins.

The 43 ft. 5 ins. above is the net length of the belt, without the lap for which allowance should be made.

Strength of Belts

Belt Tension and Horse Power.—With reference to fig. 1 the power transmitted from one pulley to the other is directly proportional to the difference in tension (T_1-T_2) and the speed of the belt.

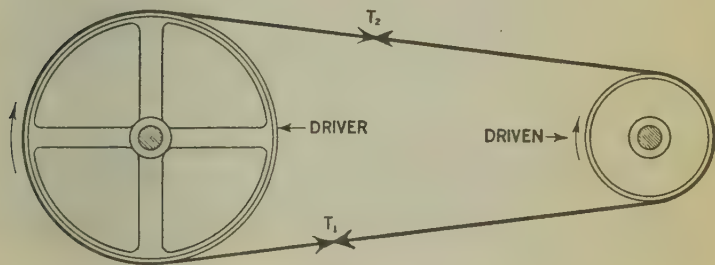


FIG. 1.—Illustrating belt tension in typical belt drive.

If (T_1-T_2) be measured in pounds and the belt speed (V) in ft. per minute, the horse power (h.p.) transmitted may be written:

$$\text{H.P.} = \frac{(T_1-T_2)V}{33,000} \dots\dots\dots (1)$$

but since the speed $V = \pi \times D \times N$ it follows that

$$\text{H.P.} = \frac{(T_1 - T_2) \pi \times D \times N}{33,000} \dots\dots\dots (2)$$

where

D = pulley diameter in feet

N = revolution per min. of pulley shaft

$\pi = 3.1416$

Example.—The full load speed of a motor having a 9 in. diameter pulley is 850 *r.p.m.* If the high and low tension pulls are 150 lbs. and 30 lbs. what is the horse power transmitted to the belt?

Solution.—Substituting numerical values in the formula the horse power—

$$\text{H.P.} = \frac{(150 - 30) \pi \times 9/12 \times 850}{33,000} = 7.28, \text{ say } 7\frac{1}{4} \text{ H.P.}$$

The customary method of expressing the amount of slack side tension (T_2) necessary for a successful drive is in the form of a ratio commonly called the *tension ratio*. This ratio is written T_1/T_2 and usually varies over rather large limits, depending upon pulley diameter ratios, center distances, pulley gripping quality, type of belting employed, etc.

Millwright's Rules for Determination of Belt Sizes.—For a given condition the minimum belt width is determined by the horse power to be transmitted, and the speed of the belt.

The millwright's rules are as follows:

Rule I.—A single belt 1 in. wide, running at 800 ft. per min. will deliver approximately 1 horse power (up to about 4000 *r.p.m.*).

Rule II.—A double belt 1 in. wide, running at 500 ft. per min. will deliver approximately 1 horse power (up to about 4000 *r.p.m.*).

These rules will give wide margins of safety in ordinary power transmission when the speed of the belt does not exceed 4000 ft. per min. Above this speed the centrifugal effects due to the belt weight begin to be rather appreciable and should therefore be included.

For heavy transmission and speed exceeding 4000 ft. per min. the above rules should be checked with the manufacturers' recommendation.

As it is more convenient for calculation purposes to express rules in algebraic forms, thus for single belts,

$$Bw = \frac{H.P. \times 800}{V} \dots \dots \dots (3)$$

where,

Bw = Belt width in inches

V = Belt speed in ft. per minute

H.P. = Horse power transmitted

Similarly for double belts,

$$Bw = \frac{H.P. \times 500}{V} \dots \dots \dots (4)$$

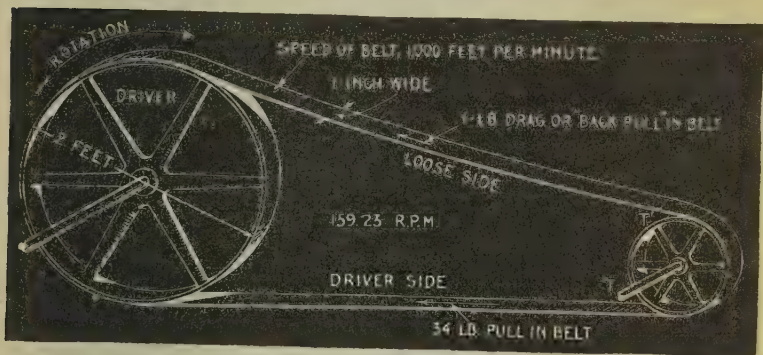


Fig. 2.—Illustrates a belt transmitting one horse power. In the figure the tension in the tight side of the belt is 34 pounds and in the loose side 1 pound. The driving force is therefore = 34-1 = 33 lbs. Since the belt is traveling at a velocity of 1,000 ft. per min. the power transmitted = 33 lbs. $\times$ 1,000 ft. = 33,000 pound-feet = 1 horse power.

Example.—What size of double belt is required to transmit 50 horse power at a belt speed of 4000 ft. per minute?

Solution.—According to formula (4) the belt width

$$Bw = \frac{50 \times 500}{4000} = 6.25, \text{ or say } 6\frac{1}{2} \text{ in.}$$

Example.—If a single belt be used in the previous example, what will be its size?

Solution.—Substituting numerical values the width of the single belt

$$Bw = \frac{50 \times 800}{4000} = 10 \text{ inches.}$$

The ratio $\frac{10}{6.25} = 1.6$ expresses that a double belt is not considered twice

but only 1.6 times as effective as a single belt.

A useful table giving the horse power per inch of width transmitted by leather belts, is given on the opposite page. To obtain the horse power transmitted by belts of any width multiply the figure shown for the given belt speed by the width of the belt used.

Thus, for example, if the belt speed be 4000 ft. per minute and the width of the double belt be $6\frac{1}{4}$ in. multiply the figure corresponding to a speed of 4,000 ft. per min. with the width of the belt to obtain the horse power transmitted or,

$$6.25 \times 7.94 = 49\frac{5}{8}, \text{ say } 50 \text{ H.P.}$$

Again if the horse power to be transmitted and the belt speed in ft. per min. be known, divide the figure shown for a given belt speed, with the known horse power to be transmitted, to obtain the belt width necessary.

Example.—An electric motor rated at 10 H.P. has a full load speed of 1150 *r.p.m.* and a pulley diameter of 8 in. and is to drive a drilling machine by means of a belt. What width of single belt is required?

Solution.—Since the speed of the motor is 1150 *r.p.m.* and its pulley diameter 8 in. it is necessary to first find the belt speed in ft. per minute. This will conveniently be found by remembering that the belt speed (V) is equal to $\pi \times D \times N$, where

$$\pi = 3.1416$$

D = Pulley diameter in ft.

N = Revolutions per min. of motor

Thus

$$V = \pi \times \frac{8}{12} \times 1150 = 2,410 \text{ ft. per min.}$$

By consulting our table, the figure corresponding to a belt speed of 2,410 is most nearly 3.33; by dividing this figure by the horse power transmitted to the belt, the width of the belt is finally obtained thus,

$$\text{Belt width (single)} = \frac{10}{3.33} = 3 \text{ inches}$$

Belt Speed, Ft per Min	Hp per Inch of Width	Belt Speed, Ft per Min	Hp per Inch of Width	Belt Speed, Ft per Min	Hp per Inch of Width	Belt Speed, Ft per Min	Hp per Inch of Width
Single Belting							
900	1.25	2000	2.78	3100	4.31	4200	5.84
1000	1.39	2100	2.92	3200	4.45	4300	5.98
1100	1.53	2200	3.06	3300	4.59	4400	6.12
1200	1.67	2300	3.20	3400	4.72	4500	6.26
1300	1.81	2400	3.33	3500	4.86	4600	6.40
1400	1.95	2500	3.47	3600	5.00	4700	6.54
1500	2.09	2600	3.61	3700	5.14	4800	6.68
1600	2.22	2700	3.75	3800	5.28	4900	6.82
1700	2.36	2800	3.89	3900	5.42	5000	6.96
1800	2.50	2900	4.03	4000	5.56	...	....
1900	2.64	3000	4.17	4100	5.70	...	....
Double Belting							
900	1.79	2000	3.97	3100	6.16	4200	8.34
1000	1.99	2100	4.17	3200	6.36	4300	8.54
1100	2.19	2200	4.37	3300	6.55	4400	8.74
1200	2.39	2300	4.57	3400	6.75	4500	8.94
1300	2.58	2400	4.77	3500	6.95	4600	9.13
1400	2.78	2500	4.97	3600	7.15	4700	9.33
1500	2.98	2600	5.16	3700	7.35	4800	9.53
1600	3.18	2700	5.36	3800	7.55	4900	9.73
1700	3.38	2800	5.56	3900	7.74	5000	9.93
1800	3.58	2900	5.76	4000	7.94	...	....
1900	3.78	3000	5.96	4100	8.14	...	....

Pulley Diameters vs. Belt Thickness.—The smallest diameters of pulleys over which belts of various thicknesses will work satisfactorily, vary with the care with which the belt is manufactured, as well as the grade of material involved.

The thickness of various types of belting in relation to minimum pulley diameters is given in the following table.

TYPE OF BELT	THICKNESS (Inch.)	MIN. DIA. OF PULLEYS (Inch.)
LIGHT SINGLE	$\frac{1}{8}$ to $\frac{5}{32}$	3
MEDIUM SINGLE	$\frac{5}{32}$ to $\frac{3}{16}$	4
HEAVY SINGLE	$\frac{3}{16}$ to $\frac{7}{32}$	5
LIGHT DOUBLE	$\frac{1}{4}$ to $\frac{9}{32}$	6
MEDIUM DOUBLE	$\frac{5}{16}$	10
HEAVY DOUBLE	$\frac{3}{8}$	16
MEDIUM THREE PLY	$\frac{1}{2}$	30
HEAVY THREE PLY	$\frac{9}{16}$	36

Belt Joints

Methods of Making Belt Joints.—There are several methods by means of which belting is made endless, such as:

1. Cementing.
2. Lacing, which may be sub-divided into various classes such as *lap*, *butt* and *apron* joints.
3. Patented hook and plates.

However, before proceeding with the various methods of joint making, it may be well to repeat that the safest method to determine the length of a belt is by direct measurement over the pulleys with a steel tape.

If the old belt is present, measure over it and deduct from the tape line measurement six times the belt's thickness.

Making a Cement Joint.—After the required length has been measured off, a sufficient amount of length should be added to prepare for the necessary laps. These will vary with the width of the belt to be installed. For single belts the practice is to use a 4 inch lap for belts up to 3 inches in width and 6 inch laps for belts exceeding this width. It should however be remembered that extra heavy belts or extra light belts may call for longer or shorter laps.

The laps in either single or double belting should be tapered carefully with a special plane or drawing knife upon a level surface to assure a good and even performance.

Leather should be cleaned from oil and grease before application of cement. After the two edges have been thoroughly cleaned the cement is spread over both pieces and put together, and a suitable pressure applied until the cement has set. The lap should be allowed to dry undisturbed for ten to fifteen minutes and should not be put in use for one to two hours after sticking.

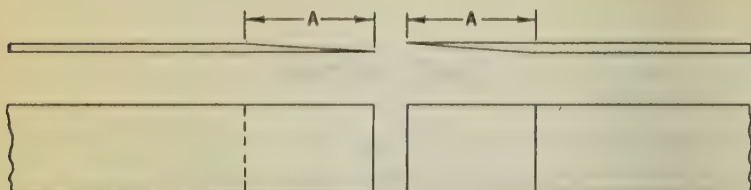


FIG. 1.—Method of splicing a single belt by means of cement. For belts three inches wide make $A = 4$ inches; for belts exceeding this width make $A = 6$ inches.

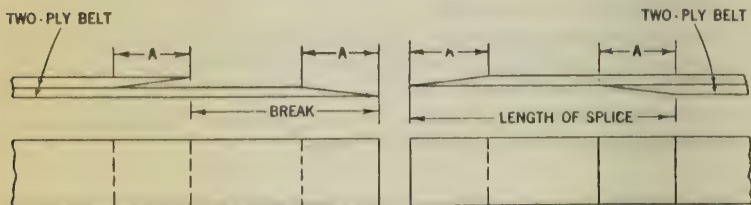
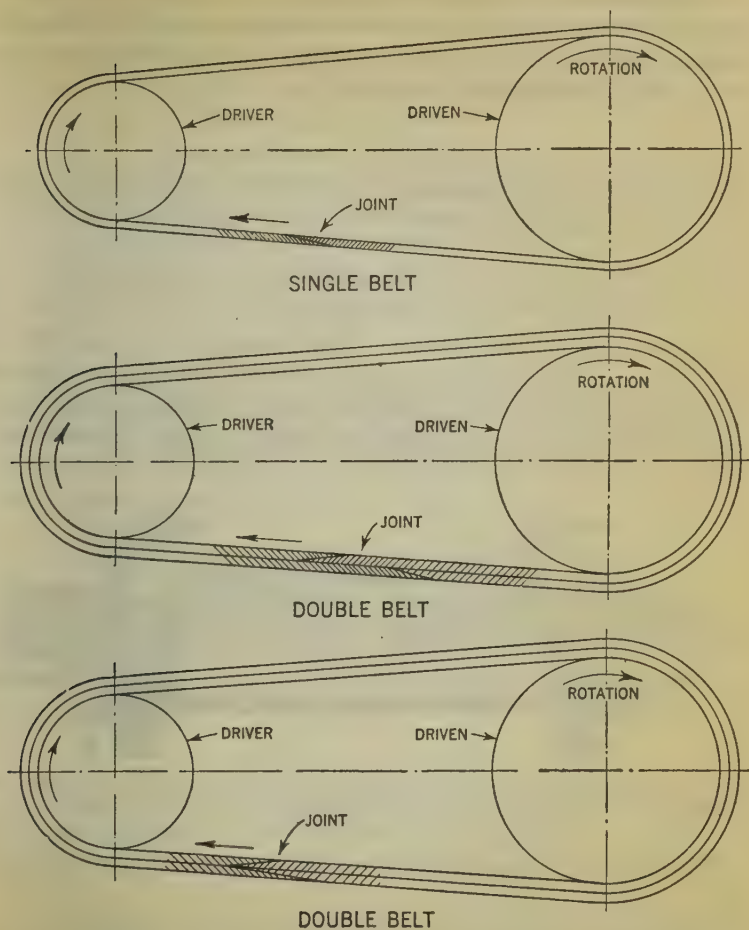


FIG. 2.—Method of splicing a double belt by means of cement. In this method two single laps are prepared with a *break* between as a means of staggering the laps in the two plies. The length of lap A , is generally made three to four inches long, depending upon the width of the belt. The break should be approximately 2 inches less than the width of the belt, but should not be less than 5 inches and not more than 24 inches.

Making Cement Joints on Double Belts.—When making joints in double belts the same general procedure is followed as that already described for single belts. With reference to illustrations shown, the belts and lap are made up with one male and one female and prepared in such a manner so as to eliminate any possibility of uneven thickness throughout.



FIGS. 3 to 5.—Showing proper direction of overlap in joint with reference to direction of travel and pulley surface, in various methods of joining. A simple rule easy to remember, is that all belts should be made up and applied to the pulley in such direction that the point of the lap on the outside of the belt is pointing away from the pulley it is approaching.

Belt Clamps and Their Use.—When joining heavy belts and especially those which have to be cut rather short to allow for stretching, it is convenient to use some sort of belt clamps to facilitate the joinings of the end.

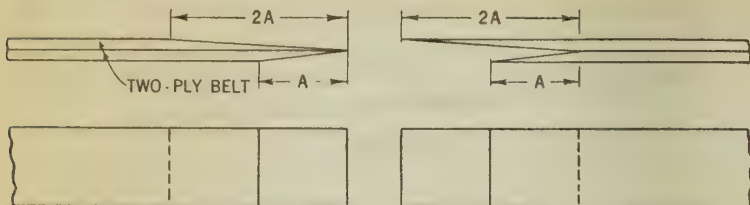


FIG. 6.—This method differs from that previously shown in that at one end the two laps are cut to a point—the one end being cut to twice the length of the other. When the belt is cut in this manner the length represented by $2A$ should be 8 inches for belts less than 5 inches wide, and 12 inches for belts 5 to 12 inches wide. For belts over 12 inches wide, the length of the lap should be equal to the width of the belt with a maximum of 24 inches.

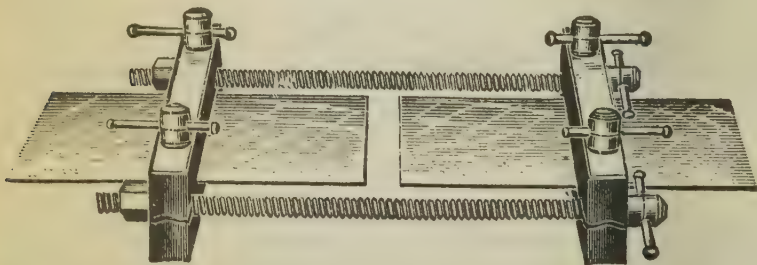


FIG. 7.—Arrangement of belt clamps used to hold belt securely in position when making up joints.

The general arrangement of such a device is illustrated in fig. 7.

It consists essentially of two pair of blocks equipped with a slight tongue and groove together with bolts for tightening the belt.

After insertion of the belt in such a manner so as to allow for joining clearance, the clamps are securely fastened and pulled together by means of the two main rods (4 to 10 ft. long) equipped with right and left hand thread with large nuts on one end and vise handles on the other.

When fastening the clamps on the belt, precaution should be taken that the clamps be at right angles with the belt and correctly centered with it. The main rods should be taken up both evenly and simultaneously in order that the ends to be joined may fit together correctly.

A press block of suitable size consisting of two blocks with flat surfaces and take up bolts will facilitate the application of pressure on the cemented joint.

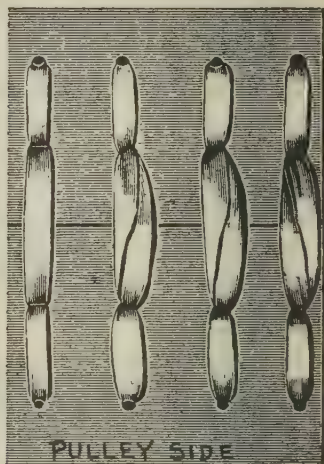
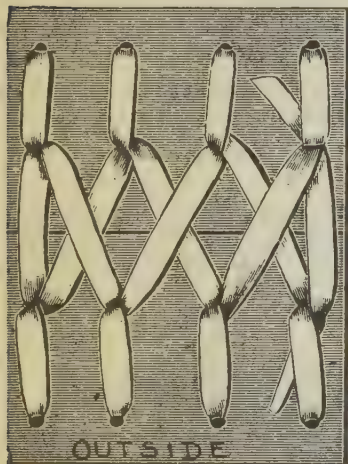
Making a Laced Joint.—The best lacing material consists of *raw hide* or *Indian tanned lace*. The laced joint is used very frequently when leather belting is being employed, its advantages over other types being:

1. They are made more rapidly than other types.
2. If correctly made they are very strong.
3. The absence of a metallic surface against the pulley increases the efficiency of the belt.
4. They prevent injury of the hands of the operator when a shifting is necessary.

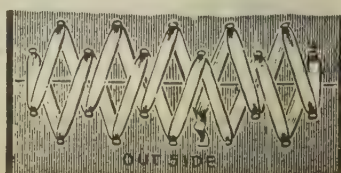
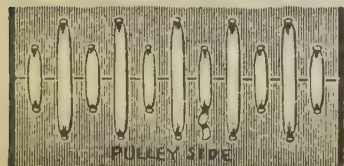
Although there are no specific rules in making a laced joint for various sizes, a good method of lacing a leather belt is as follows:

The first row of holes is punched one inch from the end of the belt, and the second row two inches from the end. The number of holes across the belt should equal the number of inches in the width, with the holes on the side $\frac{3}{8}$ inch from the edge. The lacing should always be made with the flesh side out and the grain side in or towards the pulley.

Commencing the lacing from the side of the belt, the ends being passed from the inside, each end is then passed through the hole in the opposite end of the belt, making two thicknesses of lacing on the inner side. Each lacing end is then passed through the hole in the back row and again through the same hole as before in the first row, thus filling the four holes at the side and leaving the lacing straight with the length of the belt.

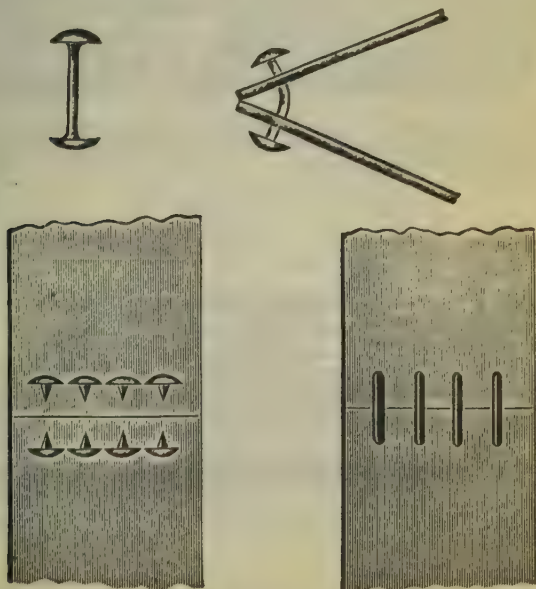


FIGS. 8 and 9.—A good method of lacing a 4 inch belt is shown in fig. 8 which represents the outside appearance. The smooth finish of the inside of the belt is shown in fig. 9. The lacing used is $\frac{5}{16}$ inch oil tanned leather.



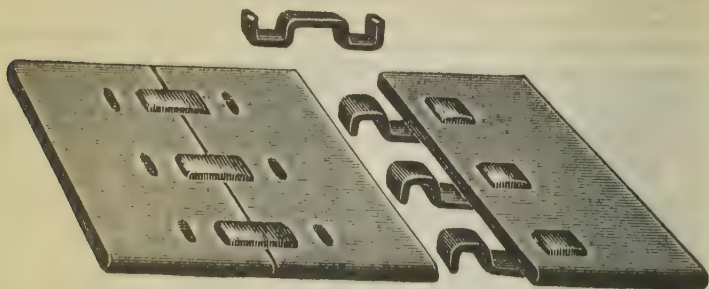
FIGS. 10 and 11.—Shows a simple and reliable method of lacing a belt joint for use with India rubber belting.

Both ends of the lacing now being on the inside of the belt, they must be put through the second hole in the first row on the opposite end, thus causing the lacing to cross on the back or inside of the belt. The ends are now put through these same holes again, opposite end through opposite hole, making two strands of lacing between this set of holes in the face side, the strands being straight with the length of the belt. The ends again being on the back of the belt are now to be put through the second row of holes and again through the corresponding holes in the first row, which brings the ends again to the back side of the belt ready to be crossed as they are put through the next set of holes, and so on until all the holes are filled. This makes a lacing double on the outside and smooth single strands crossing on the back and a straight pull on each strand on the face as it passes through each of the four holes in line.



FIGS. 12 to 15.—Illustrating method of belt jointing by means of belt studs (fig. 12). The studs are most frequently used with rubber belting of the lighter type, where the ends of the belt are kept close together. Here suitable slits are cut in the material parallel to the length of the belt and the fastening (studs) inserted as shown in fig. 13, after which the belt is formed to position as shown in fig. 14. When a belt is made endless in this manner, care should be taken that the cut stops from $\frac{1}{4}$ to $\frac{3}{8}$ inch short of the end of the belt.

As the lacing is drawn through each of the four holes, the ends will be found securely fastened, and will bear a strand or two being cut. It is necessary to use pliers to draw the laces through the holes.



FIGS. 16 TO 18.—Belt fastener, fig. 17, frequently used on rubber belts. The fastener has a substantial double bearing in each piece of the belt and consequently there is less risk of tearing away the fabric at the corners of the holes.



FIG. 19.—Shows a patented type of belt fastener used in making light single belts endless.

Hook and Plate Joints.—There are numerous types of patented wire hook and plate joints, frequently put in place by machines manufactured for this particular purpose, the usual forms of which are shown in figs. 12 to 19.

Precaution should be taken, however, that the proper size is used, and also that hooks are kept away from the edge of the belt so as not to inflict injury on hands of operator when shifting the belt.

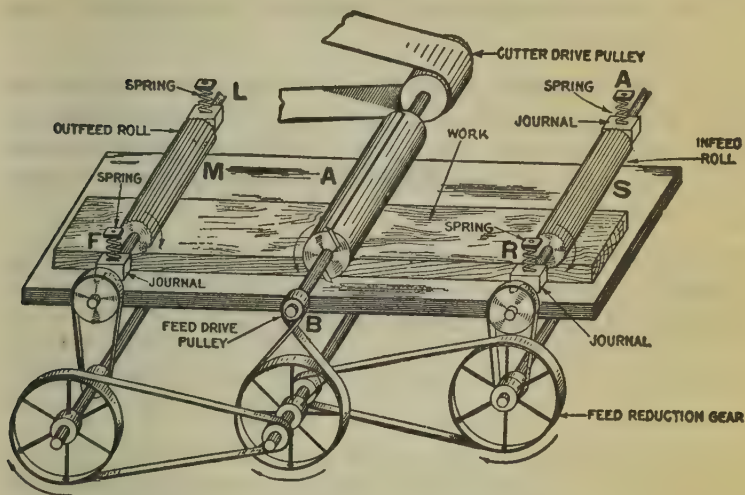


FIG. 20.—Typical application of light belts. The elementary drawing illustrates a surface planer and principle of operation. The cylinder A, containing the cutters rotates at high speed. At the end of the cylinder shaft is a small feed drive pulley B, which drives the feed rolls M and S, through the feed reduction gear so M and S, rotate at slow speed. These rolls are pressed down on the work by the spacings L, A, R, F, working through the journals as shown. The rolls being corrugated considerable grip is obtained on the work so that it is slowly pushed along the table in the direction of the arrow while the cut into the work leaves a smooth surface. The reason for two feed rolls is that the work must be fed to the cutters before it is gripped by M and must continue feeding after the end of the work leaves S, so that the entire board will be planed.

Belting Tools.—Tools necessary in belt work are: 1, belt clamps; 2, press blocks; 3, glue pot and brush; 4, shoemaker's hammer; 5, steel knife; 6, screw driver, and 7, steel awl.

Putting Belts on Pulleys.—Belts should under no circumstances be cut and spliced too short, thereby requiring undue strain to force them on the pulleys.

Because it is difficult to determine just how much a belt will stretch over a period of time, the belt should be assembled so that only a moderate amount of strain will be required to bring it on the pulleys.

If the belt be spliced too short it will almost invariably become dented at the point where it is unduly forced on, due to the unusual force on one edge, the result of which will be an unsatisfactory and weak belt, which will in addition, put an excessive strain on shafts and bearings.

In all cases where conditions are such that belts cannot readily be spliced off the pulleys, an arrangement of belt clamps such as that shown in fig. 7 will have to be employed.

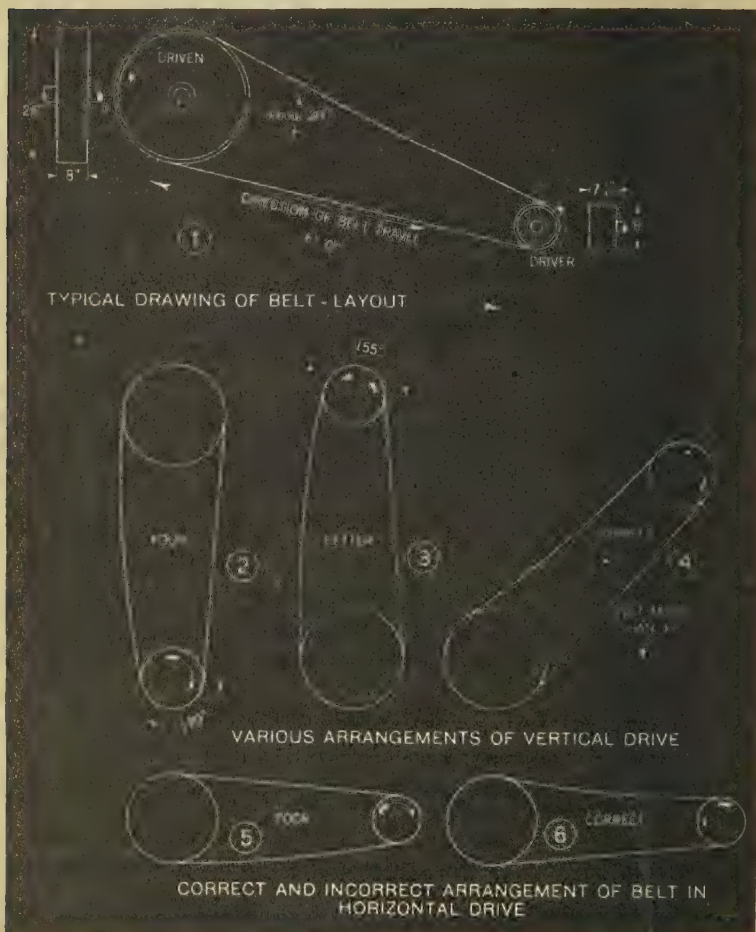
Drive Arrangements

Drive Arrangements.—*Horizontal* drives are always the best. The proper procedure here is to arrange the belt as shown in fig. 6, that is, with the *lower side* of the belt *driving*—the sag of the upper side tends to increase the *arc* of contact on the pulley. This sag should be about $1\frac{1}{2}$ ins. for every 10 ft. of center distance between the shafts.

If too loose the belt will have an unsteady flapping motion which will injure both belt and machinery. Again, if too tight, the bearing will be put under a severe strain and the belt will be quickly destroyed.

Vertical drives arranged as shown in figs. 2 and 3, should be avoided whenever possible. This is particularly true where the lower pulley is the smaller.

The reason why vertical drives prove less satisfactory than horizontal ones, is because in the vertical drive the effective tension and arc contact are substantially reduced, and as a result the slip will increase in extreme cases to the point where the normal load cannot be carried.



FIGS. 1 TO 6.—Typical belt layout and various drive arrangements.

Fig. 4 illustrates how in the best arrangement the angle should not exceed 45 degrees.

In group drives where several belts transmit power from a line shaft, it is advantageous wherever possible to locate the drive shaft so that the bearing pressure can be equalized and reduced by alternating the direction of drive first on one side and then on the other.

Belt Information.—For the purpose of estimate and recommendation, it is important that the information shown in the table be supplied. In addition to the data therein, it is well also to give such conditions as: Average temperature; moisture; angular drive; grit or dust in air; acid fumes, etc.

NECESSARY INFORMATION FOR ESTIMATE AND RECOMMENDATION OF BELT DRIVE	
HORSE POWER TRANSMITTED	INSERT DATA
SIZES OF BOTH PULLEYS	
SPEED IN R. P. M. OF ONE PULLEY, STATING SIZE	
SHAFT CENTER DISTANCES	
BELT, OPEN OR CLOSED	
TYPE AND POSITION OF IDLERS, IF USED.	
INCLINATION OF DRIVE (Angle in Degrees)	
SLACK SIDE OF BELT (Top or Bottom)	
TYPE OF PULLEYS (Stepped or Flanged)	
NATURE OF DRIVE, TYPE OF MACHINERY,	
LOAD FLUCTUATIONS ETC.	

Belt Maintenance.—It is of paramount importance in order to secure the best possible economy that a proper maintenance schedule be observed. This consists of numerous details, the most important of which are:

1. Keeping belts tight
2. Taking up of slack belts
3. Running in new belts
4. Cleaning of dirty belts
5. Dressing of belts
6. Maintenance of belt guards

In locations where idlers or tension base drives are employed, the tightness of belts is automatically adjusted to a desired value. Due to absence of the necessary space requirements, however, this method is not always feasible, and the surplus length will therefore have to be removed at certain intervals of time.

Some belts stretch more than others under similar conditions and loads.

The temperature and humidity are two factors which greatly influence the tension of belts. Locations of high humidity and moisture are known to cause a belt to expand more quickly.

Putting New Belts in Service.—Before a new belt be put in service, it is a good practice to run the belt under light load to limber it up. This holds good for all kinds of machinery in which power is transmitted from one part to another, and as a belt most frequently is a component part of one machine, it follows that this rule also applies when the belt is utilized as a means of transfer of power between two separate machines.

Cleaning.—In locations where there is a considerable amount of dust of one kind or another, and especially where there are particles of oil present, the belt has a tendency to lose its smoothness and become stiff and glazy, causing excessive slip and unsatisfactory operation. This accumulation of dirt should be scraped off with a suitable tool (square edge or a block of wood),

taking care that the scraping operation is performed in the direction of the point of the lap to protect against damage of the leather.

Belt Dressing and Application.—There are a great amount of belt dressings on the market, some of a very high quality, although others may actually cause damage to the belt instead of resurrecting it. The surest method of obtaining a desirable belt dressing is to purchase it from a reputable belt manufacturer.

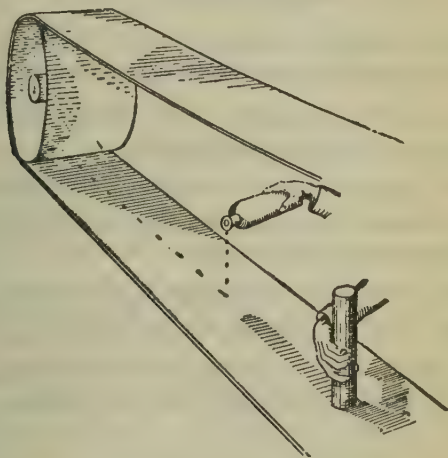


FIG. 7.—Method of applying dressing to a running belt.

The object of the belt dressing is to maintain the surface in a pliable condition to insure a gripping effect on the pulley crown.

A good belt dressing consists of tallow and cod oil melted together to form a paste which is worked in the belt by means of a suitable brush, or if the belt is running as shown in fig. 7. When

applying the dressing care should be taken not to apply an excessive amount, because this makes the belt soggy, decreasing its lateral stiffness.

An old approved recipe for belt dressing is as follows: Prepare tallow by boiling it in water, so that the latter may take up the salt and dirt, which may be poured away when cold. Re-melt the *perfectly clean tallow*, and when it is warm pour in cod oil, in the proportion of 1 gallon to each 2 lbs. of tallow, stirring until the mixture is cold. The oil *must not be boiled*, as that destroys its valuable qualities.

BELT NOTES

After the elastic limit of a leather belt is reached, it may be stretched to the breaking point without getting it any tighter.

The friction increases regularly with the pressure, the more elastic the surface the greater the friction.

To obtain the greatest amount of power from belts, the pulleys should be covered with leather; this will allow the belts to run very slack and give more wear.

The leather in a belt should be pliable, of fine close fibre, solid in its appearance, and of smooth polished surface.

Belts derive their power to transmit motion from the friction between the surface of the belt and the pulley, and from nothing else.

The thickness, as well as the width of belts, must be considered; consequently, a double belt must be used where it is necessary to transmit a greater power than possible with a single belt.

To increase the driving power of a belt, the pulleys may be enlarged in circumference, thus increasing the speed of the belt. This can often be done to advantage, provided that the speed be not carried above the safe limit.

Pulleys and Their Arrangement

Pulleys are named from their construction or to the uses to which they are put, such as:

1. **Compound pulley** by which the power to raise heavy weights is gained at the expense of speed.

2. **Cone pulley** usually stepped to different diameters to facilitate the change of speed imparted to a machine.

3. **Dead pulley**. A pulley running idle on a shaft. It is placed beside a fast or keyed pulley to receive the belt when it is thrown off the latter to stop the machine or shaft. This pulley is alternately called *loose pulley*.

4. **Two speed pulley**. A combination of two loose pulleys and toothed gearing with one fast driven pulley, whereby two different speeds of rotation may be obtained with pulleys of the same diameter by shifting the belt from the fast pulley to one of the loose pulleys. This pulley is sometimes called a *double speed pulley*.

5. **Sliding pulley**. A driving pulley to which a friction clutch is attached and placed so as to slide backward and forward on a shaft. It is used to couple and disengage machinery.

6. **Grooved pulley**. A pulley used extensively on short center drive, where it is required to use large pulley ratios.

The pulley surface is grooved in form of the letter V into which the similarly formed belt is received. This form of belt drive is commonly referred to as the *V-belt drive* or *V-drive*.

On account of the geometrical form of the belt gripping surface, this kind of pulley has a very low slip factor, and is therefore employed where a close relation between the driver and driven pulley surface speed must be obtained.

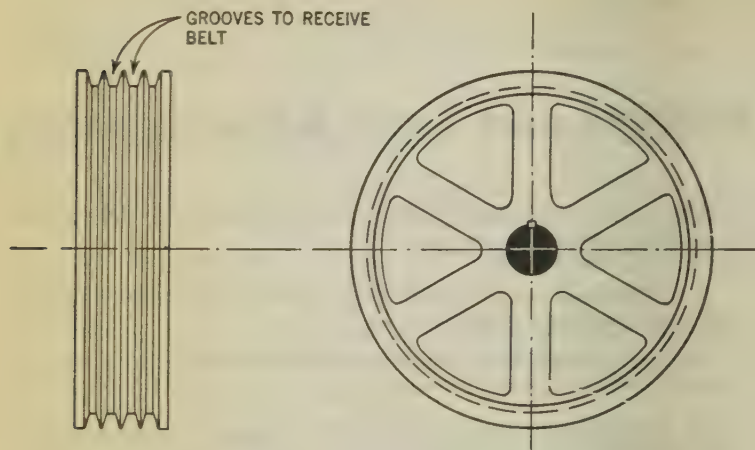


FIG. 1.—Typical grooved pulley.

Materials Used.—Pulleys are usually manufactured from cast iron, fabricated steel, paper, fiber or various kinds of wood. They are made solid or split and in either case the hub may be split so as to facilitate the assembly of the pulley with the shaft.

Comparison of Various Types.—The chief objection to wood or pulp pulleys, as compared with cast iron, is that all wood pulleys are necessarily made of built up segments, which are glued together. These segments, due to temperature and moisture changes, may come apart where the service is unusually severe. However, in ordinary use, this objection need not be considered.

The advantage of the wooden pulley is that it has a more advantageous coefficient of friction, especially when new.

Sometimes wooden and iron pulley surfaces are covered with leather, fastened by various methods. The best fastening method is to connect a smooth leather covering upon the pulley, hair side outward. The leather should be uniform in thickness, of the width of the pulley surface and of equal length to the circumference, plus the amount of lap.

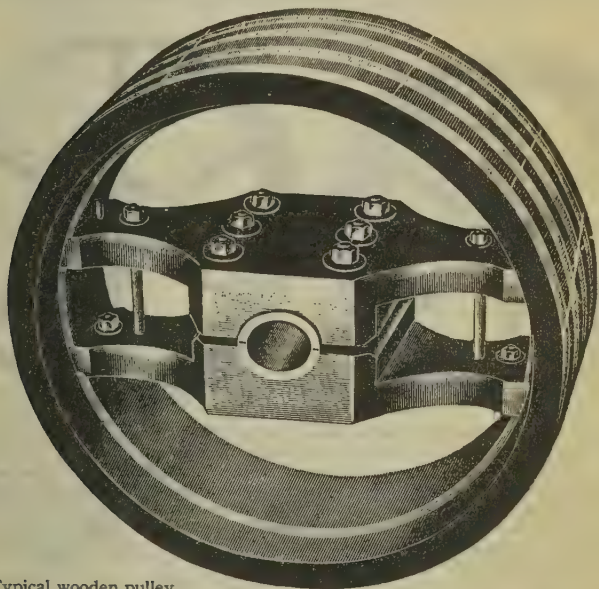
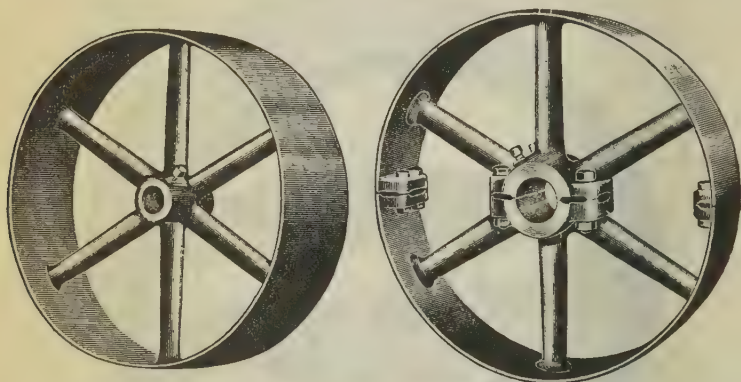


FIG. 2.—Typical wooden pulley.

The lap should be carefully scarfed so as not to raise a hump on the rim and with the point of the scarf lying in the direction opposite to that in which the pulley revolves.

Dimensioning of Pulleys.—Irrespective of the materials used, the pulleys should be dimensioned so as to transmit the power required with a conservative factor of safety. Particular pre-

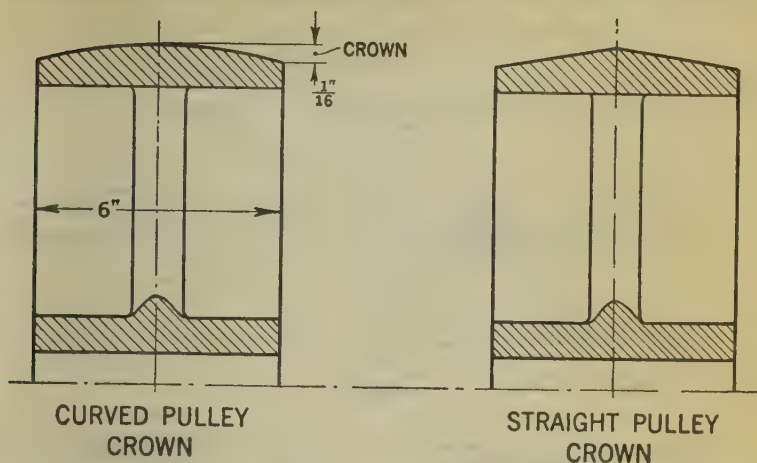
cautions should be taken with the high speed pulleys of large diameter on account of the centrifugal forces involved. Design of such pulleys is naturally outside the scope of millwrights and factory maintainers and should be performed by competent transmission engineers. In this connection it may be pointed out that it is particularly important that pulleys which run at speeds in excess of 4,000 ft. per min. be completely balanced.



FIGS. 3 and 4.—Fig. 3, represents a solid pulley, the tapered arms meeting the rim in a slightly rounded corner or fillet, and the rim being thickened at end towards its center. For heavy duty service a double set of arms is usually employed. In some types the arms and the hub are cast in one piece and the rim is formed of a band of wrought iron riveted to the arms. When this method is utilized shrinkage strains are largely eliminated and a strong and light pulley is obtained. In fig. 4, a split pulley is illustrated. Here the pulley is built up of two identical semi-circular sections, each one representing a half of the pulley, which are properly bolted together after being placed on the shaft.

Shape and Width of Pulley Surfaces.—Ordinarily pulley face widths should exceed slightly that of the belt they are to carry. It has been found good practice that the *pulley face* be approximately *one inch wider* than the belt, for belts under 12 inches wide. For belts from 12 to 24 ins., *two ins. wider*, and for belts exceeding 24 ins. in width, the pulley should be *three ins. wider* than the belt.

Flat Pulley Surfaces.—All driving pulleys which require belt shifting should have a flat surface; all other pulleys should have a crowned surface.



FIGS. 5 AND 6.—Typical cross-section of curved and straight sided crowning of pulleys. Fig. 5 shows the height of crown when the pulley width is 6 ins. Similarly the height of crown in a pulley of 9 ins. width would be $\frac{3}{32}$ in.

Crowned Pulley Surface.—The main reason for the use of crowned pulleys is that *belts adjust or center themselves* better when the pulley be given a slight crown. The crown of the belt is effective only when the slip of the belt is at a minimum because a slipping belt will run off a crowned pulley more easily than a flat faced one.

Leather belts require higher crowns than rubber or cotton belts. The form of the crown used may be either of the convex or a very slight V-form. See figs. 5 and 6. A good figure for the amount of crowning is that the height of the pulley crown be $1/96$ of the width, or $1/8$ in. per foot of pulley width.

Belt Shifters.—One of the detrimental factors of most belt shifters is that ordinarily the weight of the pole operating the shifter has a tendency to move the position of the belt so that it is partly on and partly off the loose pulley.

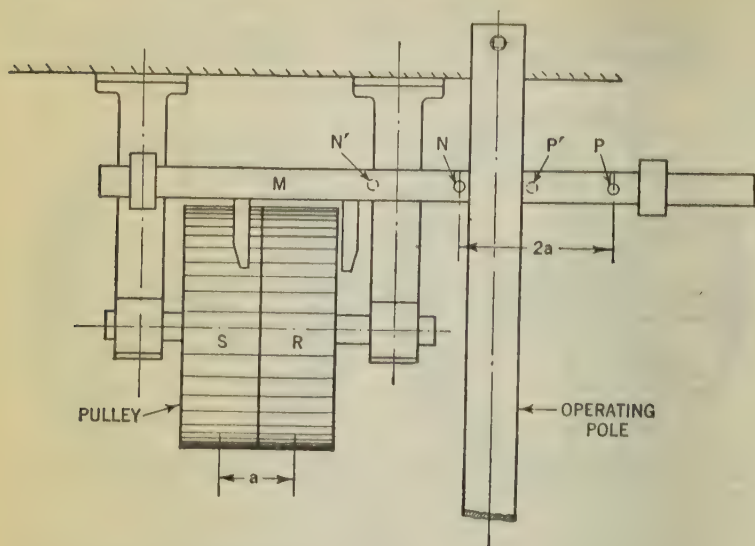


FIG. 7.—Arrangement of belt shifter.

This can easily be remedied by the arrangement shown in fig. 7. Here the pins of the fork bar **M**, are spaced apart a distance twice that through which the belt is shifted.

It is obvious from the illustration that whatever the position of the belt on either tight or loose pulley, the shifter pole hangs vertically and bears against one or the other of the pins. Thus when the pole rests against the pin **N**, it is in a position to move the belt from pulley **R** to **S**.

This transfer of the belt causes pin **N**, to move to **N'** and the pin **P**, will take up position **P'**. The shifter pole will not rest against it when the pole is released after moving the belt on to pulley **S**, thereby bringing it in a position to move the belt back to pulley **R**.

Idle Belts.—It is good practice when belts are out of service for any length of time, not to let them rest upon the shafting, but to throw them off the pulleys. This is best accomplished by a suspension hook, as shown in fig. 8.

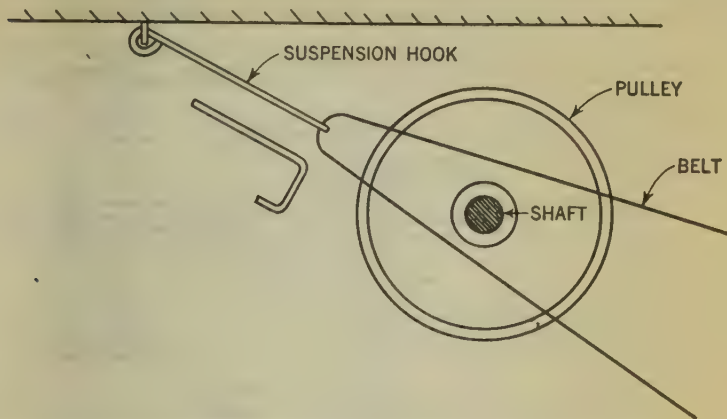


FIG. 8.—Belt suspension hook to remove belt from shafting when not in service.

The practice of having the belt resting on the shafting is not only dangerous, but also injurious to the belt. The arrangement shown consists of $\frac{3}{8}$ in. hook hanger of round iron suspended from the ceiling by a staple. The lift of the hanger should almost reach the rim of the pulley and should stretch the belt away from the shaft.

Alignment of Pulleys and Shafting.—After the motor has been properly located and the right kind of mounting has been provided, the next step will be to align the machine with its drive. The tools usually employed for alignment of machinery or line-shafting are the square, plumb bob and level.

Tool manufacturers also build combination squares and levels and similar tools that give a material aid in quickly and accurately aligning machinery. Simple useful alignment tools which are easily made are shown in figs. 9 to 12.

When two machines are to be aligned the first step is a check to find out if they are level. It is possible to be out of line in more than one plane. If by placing a level on a plumb on the machine it is found to be out a certain small amount the motor must then be mounted so that it will be out a corresponding amount.

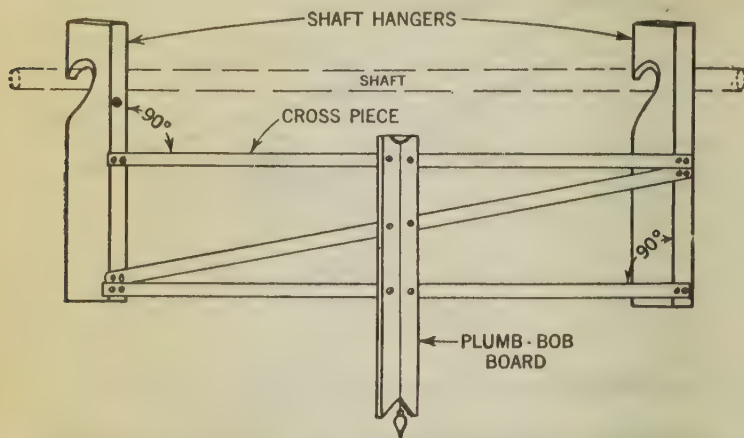


FIG. 9.—Method of shaft leveling. The two shaft hangers are fastened together as shown, care being taken to get the hangers square with the cross pieces. The plumb line board may be about 6 in. wide by 3 to 4 feet long and should be fastened to the top and bottom piece at or about the center, perpendicular to the cross pieces. When the shaft is in the horizontal position the plumb line will hang in its proper vertical position.

The illustration fig. 10 shows a simple and easy method of aligning a motor pulley with the driven pulley. First the crown or center line of the pulleys must be on the same center line, and second, the motor shaft must be parallel to the driven shaft.

By using a plumb bob, and drawing a datum line on the floor, a base of operation is established. Next, drop a plumb line from the center of the driven pulley to the floor. With a square, draw a line perpendicular to the datum line. Next drop a plumb line from the center of the motor pulley and move the

motor up or back until the plumb bob rests on the center line of the driven pulley. From the pulley center line, perpendiculars may be drawn through the centers of the holes in the motor feet. A level should be used to see that the line shafting is level. If it be not, then the motor feet must be shimmed up so that the motor shaft and the line shaft will be "out of level" the same amount. Chain drive may be aligned in a similar manner.

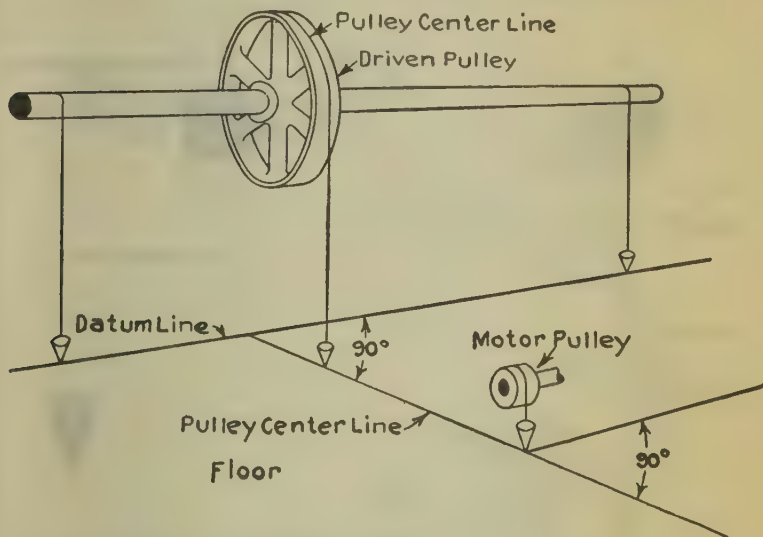
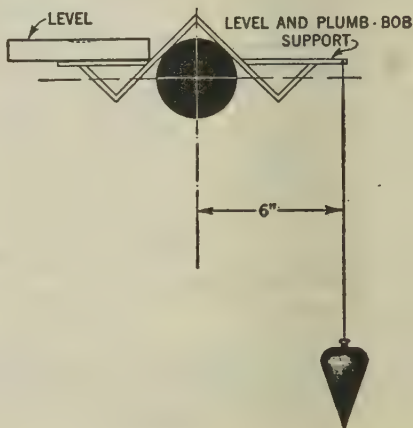
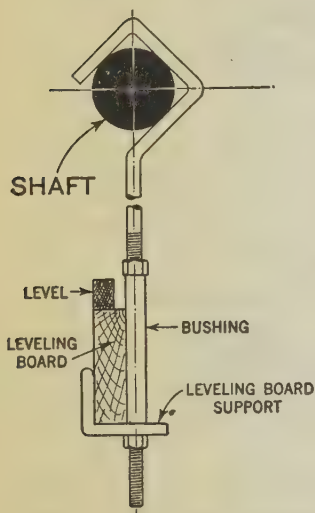


Fig. 10.—Illustrating method of aligning two pulleys.

With belt drive, a sliding base is nearly always used to allow for belt adjustment. A good method, therefore, is to use the following procedure when aligning two pulleys:

1. Place the motor on the base so that there will be an equal amount of adjustment in either direction and firmly fasten the motor to the base by means of the four holding-down bolts.
2. Mount the motor pulley on the motor shaft.

3. Locate the base and motor in approximately the final position, as determined by the length of belt.
4. Stretch a string from the face of the driven pulley toward the face of the motor pulley.
5. Parallel the face of the motor pulley with this string.
6. Using a scratch pin, mark the end positions of the sliding base.
7. Extend these lines.



FIGS. 11 and 12.—The tool shown in fig. 11 consists of two identical hooks, one of which is shown, and is made up of $\frac{3}{8}$ in. round iron. It is important that both hooks be made exactly the same, and the angle support at the other end is wide enough to receive a leveling board with parallel edges. After adjusting the angle supports to the same height when hanging side by side, perfect alignment of the shaft may be obtained by hanging the hooks from adjacent bearings and altering the screws of the latter until the level shows both panels of support at exactly the same height. The check nuts should then be tightened and the hangers are ready for use. The tool shown in fig. 12 may be made up of any convenient material. The usage of this alignment tool will not be impaired due to various diameters of shafting. By placing this tool on any length of shaft and leveling with attached level, the plumb bob will hang exactly the same distance from the center of the shaft, namely 6 in., no matter what size the shaft may be, providing the legs will straddle the shaft.

8. Move the base and motor away from the string an amount equal to one-half the difference in face width of the two pulleys. Use the two extended lines as a guide to keep the base in its proper position.

9. The belt should now be placed on the pulleys to see if it operates satisfactorily. If it does not operate properly, the base may be shifted slightly until proper operation is obtained.

10. Finally, firmly fasten the base to the floor, ceiling or side walls by means of lag screws or bolts.

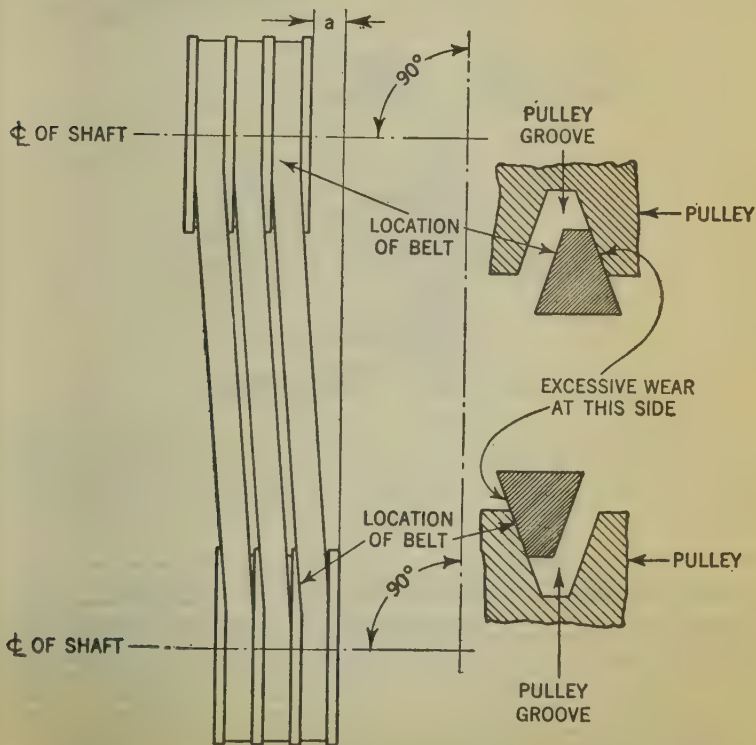
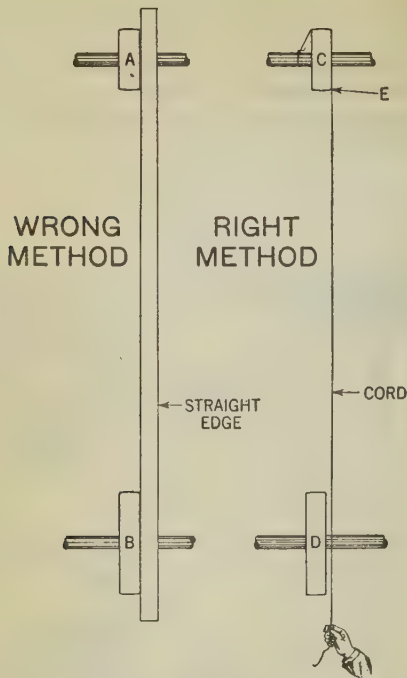


FIG. 13.—Incorrect pulley alignment resulting in excessive and uneven wear in V-belt drive. When both shafts are parallel to each other and horizontal, a correct alignment will be obtained either by moving the upper pulley through distance *a*, to the right or the lower pulley a corresponding distance toward the left.



FIGS. 14 and 15.—Two methods of pulley alignment. The straight-edge method *does not* give a satisfactory alignment because of the fact that very few straight edges are true; this will be especially noticeable if the pulley distances are large. They may have every appearance of being straight and yet be bent toward one side or the other. Sometimes they may be fairly satisfactory when lying on the floor, but when lifted up for the sake of pulley alignment, they deflect to some degree, and hence lose their dependability. A method much more satisfactory is shown in fig. 15. Here the alignment is accomplished by means of a taut wire or cord, with one end fastened around pulley shaft C, as indicated. When aligning two parallel shafts carrying pulleys, C and D, proceed as follows: Move the cord longitudinally back and forth until the cord just touches pulley edge at E, which is the correct alignment point with reference to pulley D. As indicated, the pulley marked D, will have to be moved slightly to the right, or the pulley on shaft C, moved a corresponding distance toward the left to insure correct alignment.

Mechanical Installation of Motors.—Before actual installation of an electric motor, there are several points to be considered, the most important of which are:

1. Location of the motor
2. Type of drive
3. Support of the motor
4. Atmospheric conditions

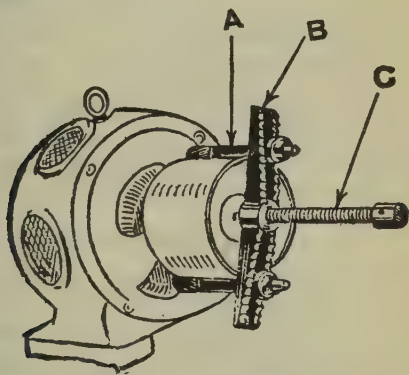


FIG. 16.—Convenient pulley removing tool. The tool consists of two links, **A**, a threaded cross-piece **B**, and screw **C**. Before force is applied to the links, care should be taken that they be located on diametrically opposite sides of the pulley and that each link be adjusted to the same length. When turning **C**, frequent tapping with a suitable wooden mallet around the circumference of the pulley will facilitate the removal and also lessen the strain on the tool itself.

The location of the motor and the drive selected are always inter-related. The best drive arrangement is that which conserves the maximum amount of floor space, and at the same time makes the motor and its control accessible for inspection and maintenance.

The support of the motor should be firm and strong and should in each case conform with the motor manufacturer's recommendations.

STANDARD DIRECTION OF ROTATION

Motors and Generators

The following rules govern direction of rotation, clockwise or counterclockwise, of generators and motors.

Standard Direction of Rotation

	Rotation	Viewed From	See Paragraph
Generators (except gas-engine-driven generators, and in motor-generators).....	Clockwise	A	1
Induction motor-generator sets (except sets with motors not having conduit boxes).....	Clockwise	C	3
Standard nonreversing d-c motors..	Counterclockwise	A	1
Synchronous motors with direct-connected exciters.....	Counterclockwise	A	1
Generators—gas-engine-driven....	Counterclockwise	A	1
Single-phase motors.....	Counterclockwise	A	1
Synchronous motor-generator sets and induction-motor-generator sets with motors not having conduit boxes.....	Counterclockwise	B	2

In all cases, the observer will stand at the designated end of the machine, facing the machine in line with the shaft.

1. *End A.* The direction of rotation of standard motors and generators will be determined by viewing the end opposite the driven end of generators, and opposite the driving end of motors.

2. *End B.* The direction of rotation of synchronous motor-generator sets, induction motor-generator sets with motors not having conduit boxes, and frequency changers, will be determined by that of the driving motor. When there are one or more generators on each end of the driving motor, the direction of rotation will be determined by viewing the motor from the connection end of the stator coils.

3. *End C.* The direction of rotation of induction motor-generator sets will be determined by that of the generator. When there are one or more generators on each end of the driving motor, the direction will be determined by viewing the set from the end which places the conduit boxes on the left-hand side.

Polyphase induction motors, except certain high-speed motors which are equipped with unidirectional fans, are suitable for either direction of rotation, which can be reversed by interchanging two leads. High-speed motors, with unidirectional fans, must be ordered for the desired direction of rotation.

CHAPTER 16

Transformer Connections

General.—Since transformers are an integral part of any power system and because the proper operation of alternating current motors depend upon the correct voltage supply it is necessary to understand the various methods used in connecting transformers and particularly how these various connections affect the voltage and current delivered from the power supply.

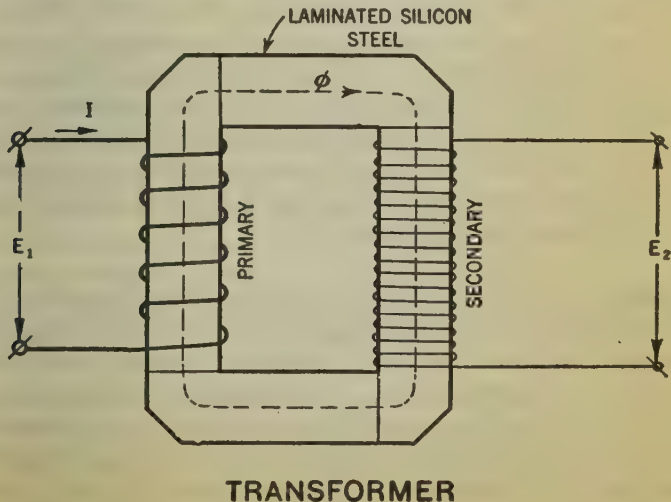


FIG. 1.—Showing windings of single-phase transformer.

A transformer may be defined as a form of stationary induction apparatus used for transferring electrical energy from one circuit to another without change in frequency.

For the sake of clearness, the following terms most commonly applied to transformers will be defined.

Primary and Secondary.—In regards to the use of the terms *high-voltage*, *low-voltage*, *primary*, and *secondary*, the *American Institute of Electrical Engineers* (AIEE) Standardization Rules read as follows:

The terms *high-voltage* and *low-voltage* are used to distinguish the winding having the *greater* from that having the *lesser* number of turns. The terms *primary* and *secondary* serve to distinguish the windings in regard to energy flow, the *primary* being that which receives the energy from the supply circuit, the *secondary* that which receives the energy by induction from the *primary*.

The terms *primary* and *secondary* are confusing, as any transformer may be used to step-up or step-down voltages. In order to avoid any misunderstanding it is preferable that the terms *high-voltage* and *low-voltage* be used instead of *primary* and *secondary*.

Ratio.—The AIEE Standardization Rules also states that: *The voltage ratio of a transformer is the ratio of the r.m.s. primary terminal voltage to the r.m.s. secondary terminal voltage under specified conditions of load.* It also defines: *The ratio of a transformer, unless otherwise specified, as the ratio of the number of turns in the high-voltage winding to that in the low-voltage winding that is, the turn-ratio.* This voltage-turn ratio is usually written as:

$$\frac{E_1}{E_2} = \frac{N_1}{N_2} = T_1 \text{ (approximately)} \quad (1)$$

Where E_1 = voltage of primary winding.

E_2 = voltage of secondary winding.

N_1 = number of turns in the primary winding.

N_2 = number of turns in the secondary winding.

T_1 = the ratio of the number of primary to secondary turns is termed the ratio of transformation (primary to secondary).

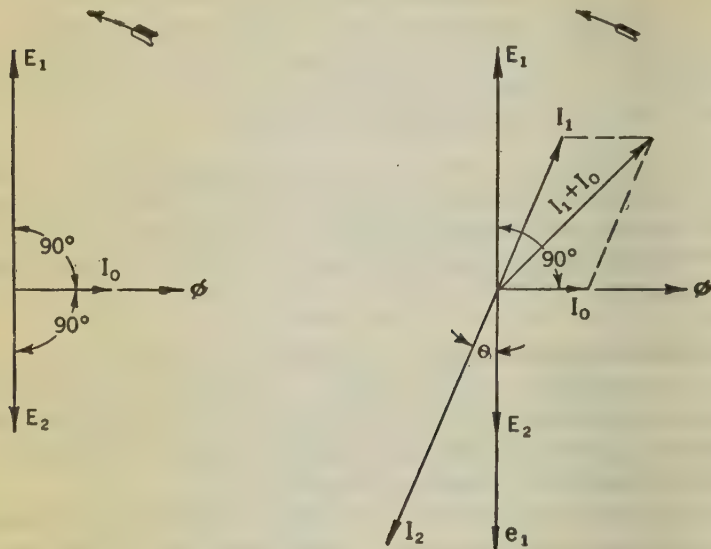
Theoretically, these two ratios are equal only when the transformer does not carry any load. When loaded, the resistance and inductance of the windings cause a drop in voltage, thus modifying the ratio of transformation slightly.

Kilovolt-Ampere Rating.—A transformer should be rated by its kilovolt-ampere (*kv-a.*) output. This output is simply equal to the product of the voltage and the current divided by one thousand ($EI/1,000$) and is the same whether the different coils are connected in series or parallel.

If the load be of unity power factor, the kilowatt is the same as the kilovolt-ampere output. If the power factor be less than unity, the available kilowatt will be correspondingly less. For example, a 100 *kva.* transformer will have full load rating of 100 *kw.* at unity power factor and 90 *kw.* at 90% power factor, etc.

Ampere-Turns.—In the case of a coil with negligible resistance, the impressed voltage leads the current by an angle of 90°, that is, the impressed and induced voltage are out of phase by 180°.

Hence, in a transformer with no current in the secondary the impressed voltage E_1 , the primary induced voltage e_1 and the current I_0 have the phase relations as shown in fig. 2, because they are both produced by the same flux.



FIGS. 2 and 3.—Vector representation of unloaded and loaded transformer, respectively.

If a load is connected across the transformer secondary, a current I_2 will flow, due to the induced voltage E_2 . The angle at which I_2 will lag or lead E_2 depends entirely upon the resistance and reactance of the load. In the vector diagram, fig. 3, I_2 is represented as lagging E_2 by an angle θ . This current sets up a flux in the opposite direction to the flux originally set in the primary winding due to I_0 .

The slightest decrease in the flux causes a corresponding decrease in the flux of the primary induced voltage. Thus, the current in the primary will increase until a magnetizing action is produced that is equal and opposite that produced by I_2 . This restores the flux to the zero or no-load value and the current remains steady again.

To produce at all times a magnetizing action in the primary equal and opposite to the secondary, I_1 must be exactly opposite I_2 and the ampere turns of the primary due to I_1 ($N_1 I_1$) must be equal to the ampere turns of the secondary $N_2 I_2$.

When a transformer is fully loaded, the ampere turns of the primary equals the ampere turns of the secondary, or

$$N_1 I_1 = N_2 I_2 \text{ (approximately)} \quad (2)$$

This equation may also be written:

$$\frac{I_1}{I_2} = \frac{N_2}{N_1} = \frac{1}{T_1} \text{ (approximately)} \quad (3)$$

Rated Current.—The *rated current* of a constant-potential transformer is that secondary current which multiplied by the rated load secondary voltage gives the *kva.* rated output. That is, a transformer of a given *kva.* rating must be capable of delivering the rated output at the rated secondary voltage, while the primary impressed voltage is increased to whatever value necessary to give the rated voltage.

Rated Primary Voltage.—The *rated primary voltage* of a constant-potential transformer is the rated secondary voltage multiplied by the turn-ratio.

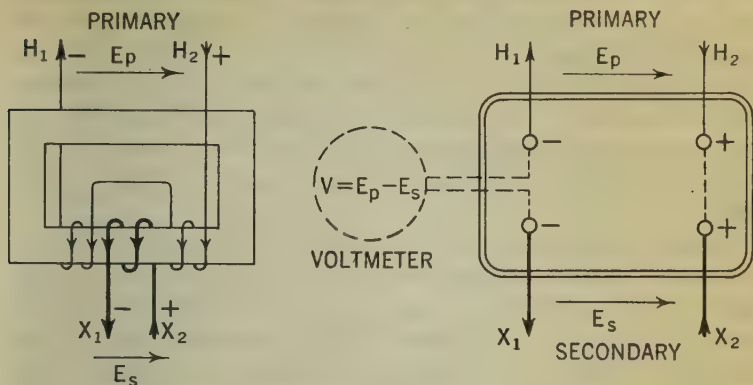
Transformer Polarity.—Since the relative direction of induced voltages, as appearing at the terminals of the windings, is dependent on the order in which these terminals are taken, in order that “polarity” may have any meaning, it must be referred to in a perfectly definite order in which the terminals shall be taken. By common usage, polarity refers to the voltage vector relations of transformer leads, as brought outside the case, and both high- and low-voltage leads being taken in the same order (from left to right or right to left) facing the same side of transformer in both cases. Thus referring to the tank sketch, fig. 5, polarity is the relative direction of induced voltage from H_1 to H_2 as compared with that from X_1 to X_2 , both being in the same order (from left to right) with respect to the tank.

Additive and Subtractive Polarity.—When the induced voltages of the high- and low-voltage sides are in opposite directions as in tank sketch, fig. 7, the polarity is said to be *additive*; when the induced voltages are in the same direction, as in tank sketch, fig. 5, the polarity is said to be *subtractive*.

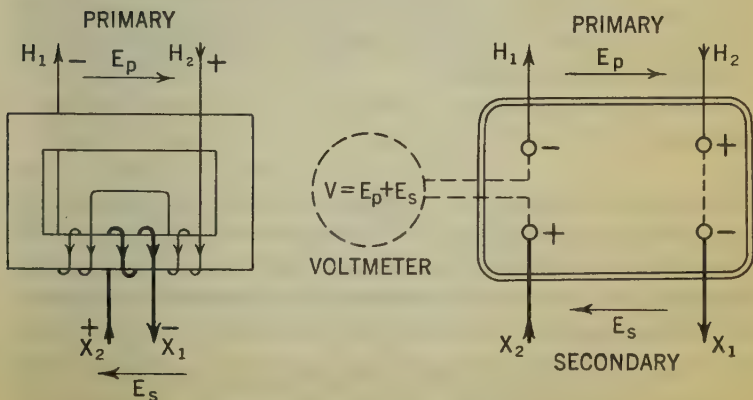
The reason for this nomenclature will be evident from the following. Referring to the tank sketch, fig. 5, if we connect a high-voltage lead to the adjacent low-voltage lead, for instance, H_2 to X_2 , and excite the transformer on either side, the voltage across the other leads, H_1 to X_1 , will be the difference of the voltages of the two sides. Following the voltage from X_1 through X_2 to H_2 and then to H_1 it is evident that the voltage H_2 to H_1 will oppose the voltage X_1 to X_2 . Hence, the polarity is *subtractive*.

Referring again to the tank sketch of fig. 7, which shows primary and secondary induced voltages in opposite directions, if we connect an H lead to the adjacent X lead, for instance,

H_1 to X_2 , and excite the transformer, the voltage across the other leads, that is, H_2 to X_1 will be the sum of the primary and secondary voltages, for reasons explained in the previous paragraph. Hence, the polarity is *additive*.



SUBTRACTIVE POLARITY



ADDITIVE POLARITY

FIGS. 4 to 7.—Illustrating method of terminal markings for subtractive and additive polarity transformer, respectively.

Testing of Polarity.—The previous definition of polarity leads to two general methods for testing the polarity of transformers.

First: With primary and secondary in series, one primary lead being connected to the adjacent secondary lead, the transformer is excited from an A.C. source on either side and the voltages across the high-voltage winding and also between the free primary and secondary terminals are measured. If the latter voltage is found to be less than that across the high-voltage winding, the polarity is subtractive; if more, it is additive.

Second: With or without primary and secondary in series, the transformer is excited from a D.C. source on either side, and a D.C. voltmeter is connected to the excited side so that a positive deflection is obtained. The voltmeter leads are then transferred directly to the adjacent terminals of the other winding without crossing. The D.C. excitation is then broken, and the inductive kick in the voltmeter observed. If the needle swings in the same direction as before, the polarity is additive, otherwise it is subtractive.

In testing for polarity, a fraction of the rated voltage is sufficient.

Marking of Leads.—It is desirable that lead designations also be indicative of polarity. This is provided for by the AIEE Standardization Rules in accordance with which high-voltage leads brought outside the case are to be marked H_1 , H_2 , etc., and low-voltage leads X_1 , X_2 , etc., the order being such that:

When H_1 and X_1 are connected together and voltage applied to the transformer, the voltage between the highest numbered H lead and the highest numbered X lead shall be less than the voltage of the full high-voltage winding.

When leads are marked in accordance with the foregoing rules, the polarity of a transformer is:

Subtractive when H_1 and X_1 are adjacent; *additive* when H_1 is diagonally located with respect to X_1 .

To simplify the work of connecting transformers in parallel it is recommended that the H_1 lead shall be brought out on the right-hand side of the case, facing the high-voltage side of the case.

Transformers having leads marked in accordance with these rules may be operated in parallel by connecting similarly marked leads together, provided their ratio, voltages, resistances and reactances are such as to permit parallel operation.

The rule can also be stated in this way: If H_1 - H_2 represents the direction of induced voltage in the high-voltage winding at a given instant, then X_1 - X_2 must be the direction of the induced voltage in the low-voltage winding. Applying this rule to figs. 4 to 7, we find that the leads are correctly lettered and that the polarities are also correct as marked.

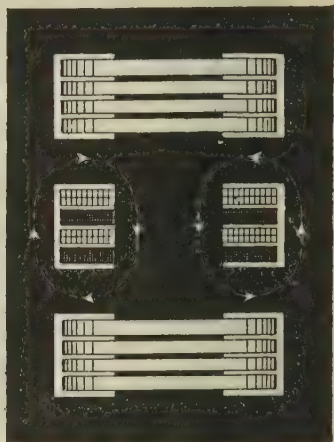
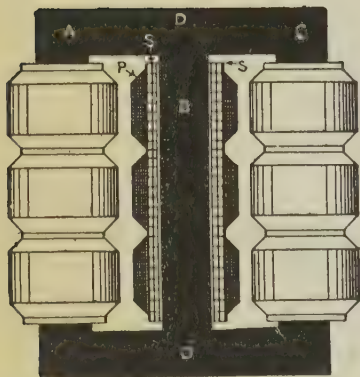
Types of Transformers.—Constant voltage transformers are made in two principal types, namely:

1. Core type.
2. Shell type.

In the former, fig. 8, the copper surrounds the iron and in the latter, fig. 9, the iron surrounds the copper. Although both types are used, the core type is best adopted for high voltages.

The core is usually formed of laminated silicon steel approximately 0.014 in. thick. Because of its high resistivity, silicon steel has low eddy current losses and also small hysteresis

losses. It may be operated at higher flux densities with a consequent saving of iron and copper.



FIGS. 8 and 9.—Core and shell types of three-phase transformer. In the *core type*, fig. 8, there are three cores—*A*, *B*, and *C*, joined by the yokes *D* and *D'*. This forms a three-phase magnetic circuit, since the instantaneous sum of the fluxes is zero. Each core is wound with a primary coil *P* and a secondary coil *S*. As shown, the primary winding of each phase is divided into two coils to insure better insulation. The primaries and secondaries may be connected *star* or *delta*. The core *B* has a shorter return path than *A* and *C*, which causes the magnetizing current in that phase to be less than that in *A* and *C* phases. This has sometimes been obviated by placing the three cores so their corners form an equilateral triangle, but the extra trouble involved is not justified as the unbalancing is a no-load condition and practically disappears when the transformer is loaded. The *shell type*, fig. 9, consists practically of three separate transformers in one unit. The flux paths are here separate, each pair of coils being threaded by its own flux which does not return through the other coils, as in the core type. This gives the shell type an advantage over the core type, for should one phase burn out, the other two may still be used especially if the faulty coils are short circuited. The effect of such short circuiting is to prevent all but a very small flux threading the faulty coil.

Connection Methods

In transforming A.C. power from one voltage to another connection of three single-phase units in polyphase banks is quite frequently made. It is necessary that before similarly marked leads of single-phase transformer units are connected together, that their *kva.* rating, ratio, voltages, polarities, resistances and reactance be the same. The three-phase transformer employed as a unit is also largely used.

Among the great variety of transformer connections in power and general power distribution work, either for straight voltage transformation or for phase transformation, the following are the most generally used:

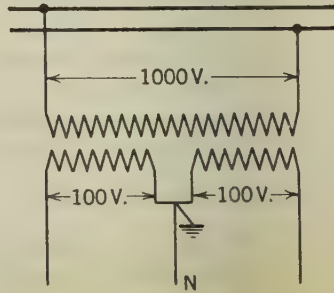
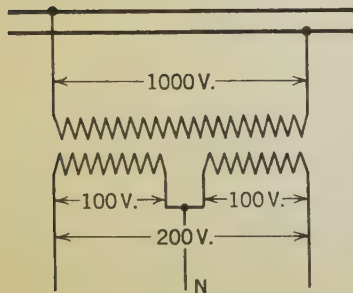
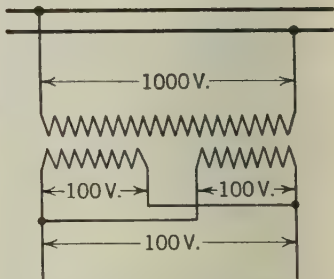
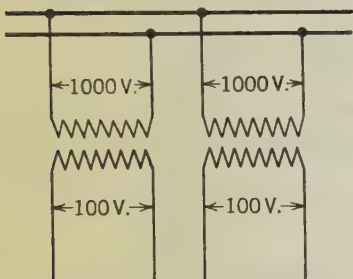
In voltage transformation:

1. Single-phase.
2. Two-phase.
3. Three-phase, delta-delta.
4. Three-phase, delta-star and star-delta.
5. Three-phase, star-star.
6. Three-phase, star-star/delta.
7. Three-phase, open-delta.
8. Three-phase, T or Scott.

In phase transformation:

1. Polyphase to single-phase.
2. Two-phase to six-phase.
3. Three-phase to two-phase.
4. Three-phase to three-phase, two-phase.
5. Three-phase to six-phase.

Single-Phase Transformers.—Here the windings may be divided into sections and variously connected to meet different requirements. For example, most standard distribution transformers are made with two low-voltage coils. Fig. 10 represents the straight connection of two transformers to 1,000 volt mains, the transformer consisting simply of single high-and-low voltage windings.



FIGS. 10 to 13.—Showing various methods of connecting single-phase transformers.

Figs. 11 and 12 represent different connections of transformers which are provided with two coils. For example, in fig. 11 the two low-voltage coils are connected in parallel to supply 100 volts.*

It is often deemed advisable to operate a three-wire circuit from the low-voltage side of transformers, and thereby reduce the cost of copper for the feeders. Such a connection is represented in fig. 12, where the low-voltage coils are connected in series and their junction connected to the neutral wire. This method of connection is used very extensively and is known as the Edison three-wire system. When used for combined power and lighting load, the motors are usually connected to the two outside wires, and the lights between the outside and neutral.

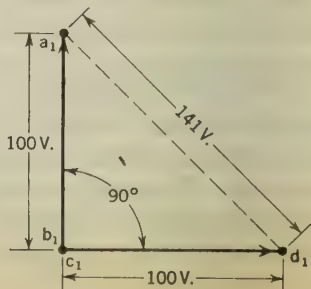
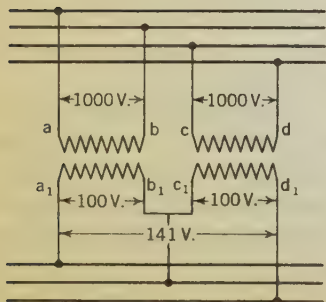
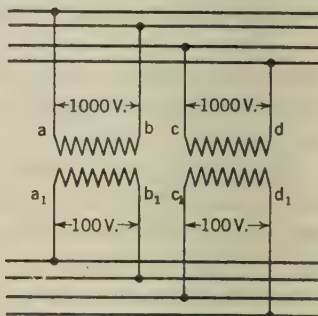
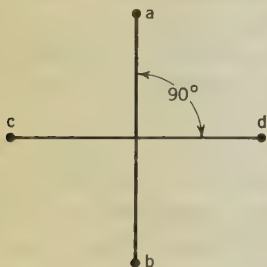
The neutral wire carries less current than the outside wires, except where the entire load is on one side. For this reason the neutral wire should be of sufficient cross-section to carry safely a current which will blow out the main fuses in case of short circuit on one side of the system.

Fig. 13 shows the three-wire distribution where a grounded-neutral wire is employed; this system is also widely used for general distribution, lighting, small motors, etc.

The four terminals of the low-voltage coils are, as a rule, brought outside the case in such proximity that they can readily be connected in any desired manner by joining adjacent terminals. Terminal boards are seldom used for the low-voltage winding of distribution transformers, because of the large current-carrying capacity required.

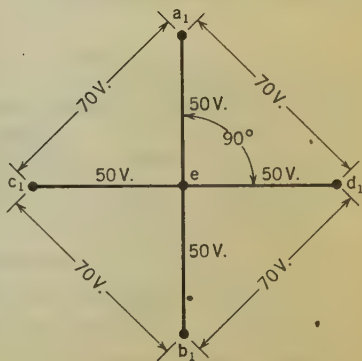
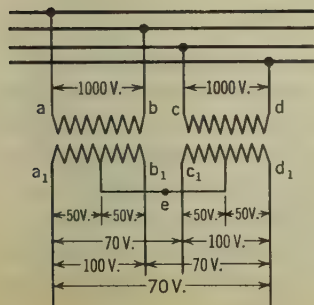
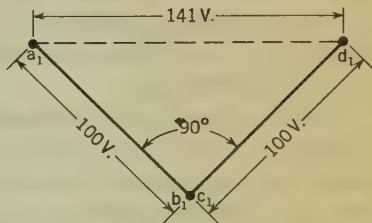
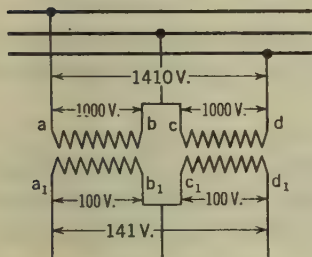
*NOTE.—The primary and secondary voltages as shown in figs. 10 to 23 do not necessarily represent standard conditions, but are shown only to give relative voltage values.

Two-Phase Transformers.—Two-phase systems practically consist of two separate single-phase circuits, with the two *e.m.f.*'s, and currents 90 electrical degrees or one-fourth of a cycle out of phase with one another as in fig. 14. Two single-phase transformers are mostly used for two-phase systems, and the most common connection are those shown in fig. 15. The high-voltage windings of the two transformers are respectively connected to the two phases of the supply mains.



FIGS. 14 TO 17.—Showing various methods of connecting two-phase transformers.

It is sometimes desirable to operate a three-wire two-phase distribution, as shown in fig. 16. In this case the voltage across the outside wires is $\sqrt{2}$ or 1.41 times the voltage of each individual transformer. This is clearly understood by a reference to the vector diagram in fig. 17, and is due to the 90° phase difference between the two *e.m.f.*'s, so that instead of adding them numerically, they must be added vectorially.



FIGS. 18 TO 21.—Illustrating various methods of connecting two-phase transformers to obtain several voltages on the secondary side of transformer.

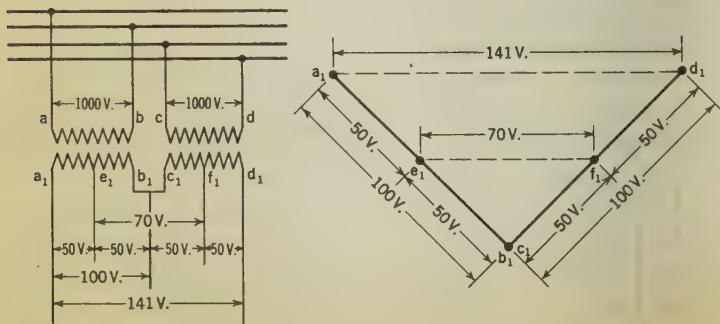
The current in the neutral wire is also 1.41 times the current in either of the outside wires, provided the load is balanced.

Transformers in two-phase work are sometimes interconnected as shown in fig. 18, where a common return is used on each side. Very few systems are operated on this plan.

By connecting together the middle points of the low-voltage windings, as shown in fig. 20, two 100-volt main circuits $a_1 c_1$ and $b_1 c_1$ are obtained. Also four 70-volt ($50 \times \sqrt{2}$) side circuits $a_1 c_1$, $c_1 b_1$, $b_1 d_1$, $d_1 a_1$.

This method of connection is used when the neutral is to be brought out in connection with Edison three-wire service of rotary converters.

Another two-phase arrangement is shown in fig. 22. It is commonly called a five-wire system. It is accomplished simply by connecting the low-voltage windings in series as in the three-wire system bringing out an extra wire from the middle point of each winding.



FIGS. 22 and 23.—Method of two-phase transformer connection for various secondary voltages.

Three-Phase Transformers.—A three-phase transformer may consist of three electrically interconnected single-phase transformers, or may be designed as shown in fig. 24, having three primary and three secondary coils wound on the same core.

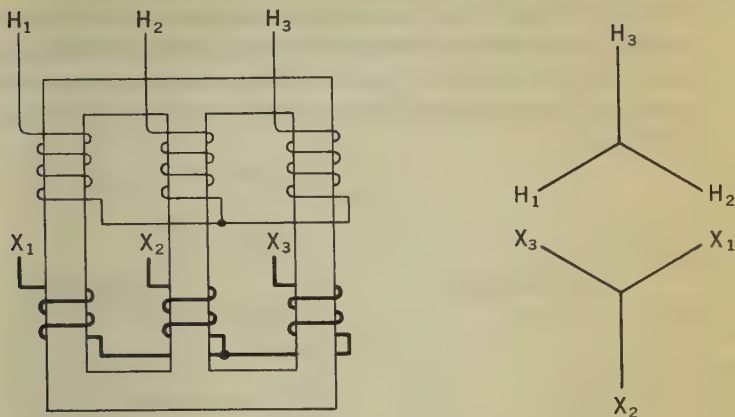


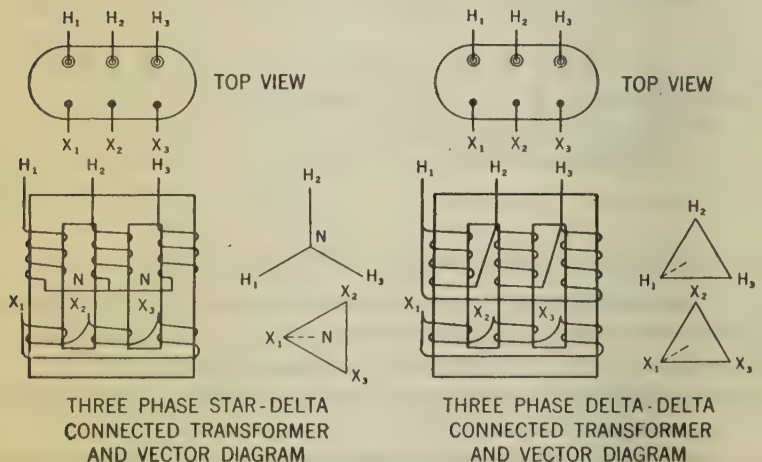
FIG. 24.—Showing a three-phase transformer unit with a star-star connection.

The choice between using a three-phase unit, or three single-phase transformers is governed largely by service requirements. The cost of one three-phase transformer is less than that of three single-phase transformers, serving the same purpose and it has a higher efficiency.

In the use of single-phase transformers in delta connections, one transformer unit may be removed without interrupting the performance of the circuit, until the damaged transformer has been repaired. The desire to obtain immunity from a shut-down caused by the failure of one of the units has led to the extensive use of delta connections, especially on the low voltage side of the circuit.

Construction of Voltage Diagrams.—With reference to figs. 25 to 32 the method used in construction of three-phase voltage diagrams are as follows:

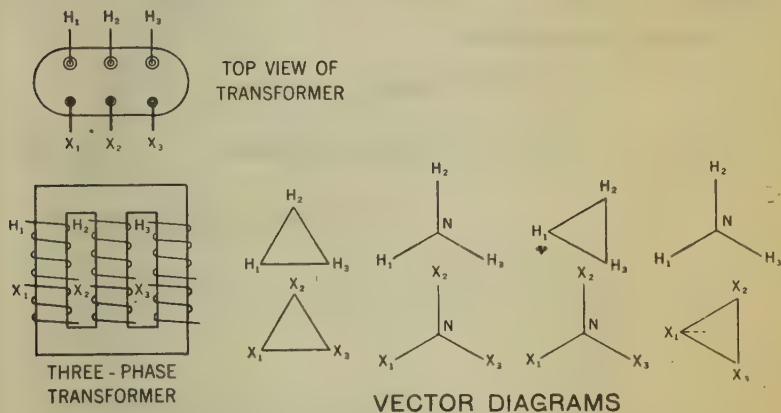
Fig. 27 represents a star-delta connected three-phase unit. Draw $H_1 H_2 H_3$, fig. 28, representing the induced voltages of the star connected winding. The voltage diagram of the delta connected winding can now be drawn. Coils X_1-X_2 , and H_1-N , fig. 27, being wound in the same direction, their induced voltage must also be in the same direction.



FIGS. 25 TO 32.—Representing two three-phase transformers, connected star-delta and delta-delta, respectively.

Therefore, we draw X_1-X_2 , fig. 29, parallel and in the same direction as H_1-N . On the middle leg, fig. 27, coil X_1-X_3 is wound in the same direction as H_2-N , and their

respective voltages are drawn parallel and in the same direction, figs. 27 and 29. Similarly for the third phase, and the diagram is thus completed. If the delta were improperly formed in fig. 27, the delta in fig. 29 would not close, showing that there would be an unbalanced voltage short-circuited through the delta. Other voltage diagrams may be constructed in a similar manner.



FIGS. 33 to 42.—Chief three-phase connections are delta-delta, star-star and delta-star (or star-delta).

Voltage Relations in a Star-Connected Three-Phase Transformer.—In a three-phase transformer circuit, fig. 43, there are two voltages between which a sharp distinction should be made. The voltage between the phase conductors and the voltage from the phase conductors to neutral (or ground where the neutral is at ground potential).

If the voltage between any one of the phase conductors be denoted as E_p and the voltage between any one of the phase conductors and ground as E_o , we may write:

$$E_p = E_o\sqrt{3} \text{ volts} \quad (4)$$

and

$$E_o = \frac{E_p}{\sqrt{3}} \text{ volts} \quad (5)$$

Thus the voltage between the phase conductors is approximately 1.73 times that between the phase conductors and ground.

The power converted is:

$$P = 3E_oI \cos \phi$$

or

$$P = \sqrt{3} \times E_pI \cos \phi \text{ watts} \quad (6)$$

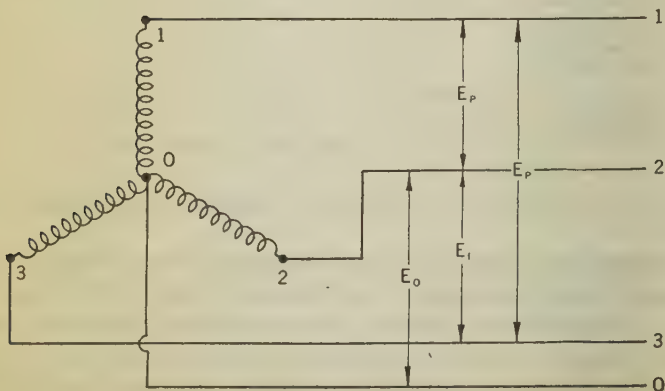


FIG. 43.—Conventional diagram of a three-phase star connected transformer.

Current Relations in a Delta-Connected Three-Phase Transformer.—If a three-phase transformer is connected as shown in fig. 44, a sharp distinction should be made between the current in each phase conductor and that of the winding.

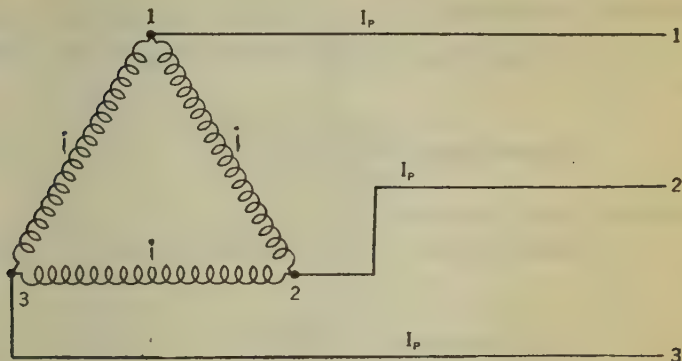


Fig. 44.—Three-phase delta connected transformer.

If the current in each phase conductor is denoted as I_p and that in each winding as i , we obtain:

$$I_p = i\sqrt{3} \text{ amperes} \quad (7)$$

and

$$i = \frac{I_p}{\sqrt{3}} \text{ amperes} \quad (8)$$

In other words, the current flowing in the phase conductor is approximately 1.73 times that flowing in the winding. The power converted is:

$$P = 3Ei \cos \phi$$

or

$$P = \sqrt{3}EI_p \cos \phi \text{ watts} \quad (9)$$

Comparison of the Two Systems.—In the case of two identical three-phase transformers connected in delta and star, respectively, we obtain:

$$\text{Delta-voltage} = \sqrt{3} \times \text{Star-voltage} \quad (10)$$

and

$$\text{Star-voltage} = \frac{\text{Delta-voltage}}{\sqrt{3}} \quad (11)$$

Similarly

$$\text{Star-current} = \sqrt{3} \times \text{Delta-current} \quad (12)$$

and

$$\text{Delta-current} = \frac{\text{Star-current}}{\sqrt{3}} \quad (13)$$

Auto Transformers.—The auto transformer differs from the previously discussed types in that it has only one winding. With reference to fig. 45, part of the load current is supplied by the secondary and a part flows conductively from the primary.

The load current is the result of I_1 and I_2 combining at point b . The ratio of voltage is:

$$\frac{E_1}{E_2} = \frac{N_1}{N_2} \quad (14)$$

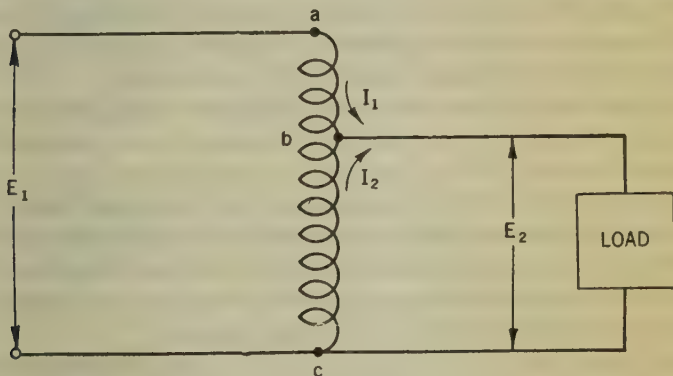
Where N_2 is the number of turns between b and c and N_1 is the number of turns between a and c .

The power represented by the current I_1 dropping in potential from a to b , is transferred to the magnetic circuit and reappears

as the power necessary to raise I_2 to the potential from c to b . The ratio of the power transformed, to the total power is:

$$\frac{N_1 - N_2}{N_1} = 1 - \frac{N_2}{N_1} \quad (15)$$

For small ratios of transformation, that is, N_2/N_1 is near unity, but a small proportion of the total power is transformed, hence there is a great saving in the cost of the transformer.



AUTO - TRANSFORMER

FIG. 45.—Schematic circuit diagram of auto transformer.

For larger ratios of transformation, however, the economical advantage is very small to which must be added the disadvantage of the low voltage winding being directly connected to the high voltage winding.

They are used for small ratios of N_2/N_1 such as $\frac{1}{2}$, $\frac{1}{4}$, etc., and are suitable for boosters on feeders for supplying reduced voltage in starting of large A.C. motors, etc.

Transformer Maintenance

General.—As compared with most electrical power apparatus, transformers require relatively little attention. This is not a reason for neglecting them. The conditions under which they operate will determine to some extent the frequency with which they should be inspected. A regular program of inspection should be established and rigidly carried out.

The oil should be tested for dielectric strength and the presence of sludge. If there is an indication of moisture or sludge formation, the oil should be tested further and if tests show the oil to be in bad condition, an inspection should be made on the inside of the tank for possible cause of the trouble. However, if the oil tests satisfactorily the case should not be opened but a careful inspection of all accessories should be made to see that they are functioning properly.

Any symptoms such as unusual noises, high or low oil levels, rupturing of relief diaphragm, etc., should be investigated at once.

Any increase in operating temperatures at normal load should be investigated and if the cause cannot be determined the transformer should be taken out of service and given a thorough investigation.

Transformers which have been subjected to unusually severe operating conditions such as overloads, frequent short circuits, or special units such as furnace transformers, should be inspected internally at least once a year. This can usually be done adequately by lowering the oil level and inspecting with a light through the manhole.

Classification.—Transformers may be divided into two general classes, depending upon their size, as:

1. Distribution.
2. Power transformers.

Thus a distribution transformer is one whose rating is 500 *kva.* or less. It is used for distributing power from high voltage lines to locations where a lower voltage is required.

A power transformer on the other hand, is one which is rated above 500 *kva.* It is used principally on main power lines to transform power from low to high voltage at the generator station, and from high to low voltage at various points along the line.

Grounding of Transformer Tanks.—The tank of every power transformer should be grounded to eliminate the possibility of obtaining static shocks from it or being injured by accidental grounding of winding to the case. A grounding lug is provided on the case of most transformers for the purpose of grounding the case and fittings.

Transformer Oil.—In transformers the oil provides an electrical insulating medium which also carries the heat away from the windings. The insulating oil is just as much a part of the apparatus in which it is used as any of the other materials which are built into the apparatus.

The oil used with a transformer should be either that originally supplied or an oil specifically approved by the manufacturer. The primary requirements are:

1. High dielectric strength.
2. Freedom from inorganic acid, alkali and corrosive sulphur to prevent injury to insulation or conductors.

3. Low viscosity to provide good heat transfer.
4. Good resistance to emulsion so that the oil will throw down any moisture entering the apparatus instead of holding it in suspension. Water in suspension is a menace to safe operation.
5. Freedom from sludging under normal operating conditions.

The principal causes of deterioration of insulating oil in service are water and oxidation. The oil may be exposed to moisture through condensation from moist air due to breathing of the transformer, especially when the transformer is not continuously in service. The moist air drawn into the transformer condenses moisture on the surface of the oil and on the inside of the tank.

Oxidation causes sludging, the amount of sludge formed in a given oil being dependent upon the temperature and the time of exposure of the oil to the air. Excessive temperatures may cause sludging of any transformer oil.

Few maintenance men realize how a minute quantity of water will spoil the insulating qualities of oil.

Distribution Transformers.—Very little maintenance is required for small distribution transformers, but the larger units should have the same attention as power transformers.

Small distribution transformers built some years ago, usually fail from lightning, overload or bushing breakdown.

Maintenance of bushings has been simplified by the development of a new line of replacement high voltage bushings. Most old transformers have the bushings babbitted into the tank, making difficult the removal and replacement of a damaged bushing. The new design bushings have a novel clamping device which eliminates the use of babbitt, provided the tank

wall is not too thick to permit the use of the demountable hardware.

The first thing to check in determining the condition of a transformer is the oil. Oil of normal dryness will test 22 kilovolts or higher in the standard test cup. If much lower than this value, the presence of moisture is indicated and the oil should be dried in a suitable filter press or centrifuge.

Power Transformers.—These should be regularly inspected because a failure is usually costly from the standpoint of interrupted service as well as repairs.

Large power transformers should be inspected from time to time to see that the oil is at the proper level and a sample of oil should be drawn from the bottom of the tank. The dielectric strength should be tested. Oil should not be permitted to go below 20,000 volts with 0.1 gap.

Checking Oil.—The oil should be inspected to see if there are any signs of discoloration of the oil or if there is any great amount of sludge or carbon in the oil. If the oil is heavily saturated with sludge or if the dielectric strength is low, the oil should be filtered or replaced with new oil. If the sludge is bad, then the oil should be removed.

The core, coils and terminal boards should be washed down with clean, hot oil under pressure. This can be done by using filterpress hose with filterpress pump pressure. After transformer is thoroughly cleaned then the filtered or new oil can be put in the tank.

If there is water in the oil, bushings, bushing gaskets, man-hole and handhole gaskets, and the main cover gaskets should be thoroughly inspected to determine how the water is getting into the oil and any defective gaskets or bushings should be

replaced immediately. Water-cooling coils should be carefully inspected and tested.

For water-cooling coils see that the lagging above the oil level is not injured or broken. Serious damage to the transformer may result from condensation. In the case of water cooled transformers, the rate of flow should be checked from time to time. If found to have diminished, the cause should be found and remedied.

Inspection.—All connections, both inside and outside the transformer, should be inspected occasionally to see that they are tight and to see that there is no discoloration, which would indicate “hot” connections. Any connections that show signs of having been “hot” should be thoroughly cleaned and bolted together tightly. Any tap changer contacts that have been “hot” should be cleaned and adjusted, or replaced. Be sure the tap changers are all on same position. A tap changer left between points may cause a transformer failure.

Before installing single-phase power transformers they should be checked for voltage ratio, impedance and polarity. In the event of a failure of one transformer in a bank of three transformers connected in delta-delta, it is possible to connect the remaining two transformers in open delta and operate them at 58% of the total capacity of the three transformers.

As to the regularity of inspections on large transformers, different companies may have different rules. Some companies make it a rule to inspect their large transformers at least once a year. They check the ground resistance and the circulating current, also all of the plant connections at this inspection. They give the oil a complete test. If necessary the oil is filtered. They also make a megger test of the windings and keep a record chart from year to year of the values.

Megger Readings.—Opinion varies among operators of power systems as to the minimum megger value allowable before removing the transformer from service. The minimum safe insulation resistance in megohms at different temperatures—*windings to ground*, used by one operator is given in the following table:

Voltage of Winding	20° C.	30° C.	40° C.	50° C.	60° C.
66 kv. and above	1,200	600	300	150	75
22 to 44 kv.	1,000	500	250	125	65
6.6 to 19 kv.	800	400	200	100	50
Below 6.6 kv.	400	200	100	50	25

Water Cooling Coils.—If large power transformers show excessive heating, they should be checked for overload and the oil should be examined for sludge. If the load is normal then the heating may be due to the water cooling coil becoming partially stopped up and reducing the water flow required. There may also be a heavy scale on the outside of the cooling coil. These can be cleaned by several methods.

Cleaning Inside of Cooling Coils.— 1. Use hydrochloric acid solution. Scale and sediment can be removed from a cooling coil without removing the coil from the tank. Both inlet and outlet pipes should be disconnected from the water system and temporarily piped to a point a number of feet away from the transformer, where the coil can be filled and emptied safely.

All the water should be blown or syphoned from the cooling coils which should then be filled with a solution of hydrochloric (muriatic) acid, specific gravity 1.10. Equal parts of com-

mercially pure concentrated hydrochloric acid and water will give this specific gravity.

It may be found necessary to force this solution into the cooling coils. When this is done, one end of the coil should be partially restricted, so that the solution will not be wasted when the coil is full. After the solution has stood in the coil about an hour the coil should be flushed out thoroughly with clean water. If all the scale is not removed the first time, the operation should be repeated until the coil is clean, using new solution each time. The number of times it is necessary to repeat the process will depend on the condition of the coil, though ordinarily one or two fillings will be sufficient.

As the chemical action which takes place may be very violent and may often force acid, sediment, etc., from both ends of the coil, it is well to leave both ends partially open to prevent abnormal pressure.

2. Using a solution of caustic soda and blowing it through the coils.

3. Using an electric vibrating machine to loosen scale and finish with hydrochloric acid.

4. Using hot sodium cyanide (6 oz. to one gallon water). With this method, extreme caution should be exercised in handling the sodium cyanide as it is very poisonous.

Cleaning Outside of Cooling Coils.—1. Use an electrically rotated wire brush.

2. Use a solution of caustic soda and steam.

3. Use a hand wire brush.

Immediately after all cleaning is done with acid or caustic, the coils should be thoroughly rinsed with clean water.

Methods of Drying Transformers

There are four methods that may be followed in drying out transformers:

- (a) By internal heat.
- (b) By external heat.
- (c) By internal and external heat.
- (d) By heating in oil.

(a) **By Internal Heat.**—For this method, alternating-current is required. The transformer should be placed in its case without the oil and the cover left off to allow free circulation of air. The low-voltage winding should be short-circuited and sufficient voltage impressed across the high-voltage winding to circulate enough current through the coils to maintain the temperature at from 80° to 90° C. measured by resistance. About one-fifth of normal full-rated current is generally sufficient to do this. The impressed voltage necessary to circulate this current varies within wide limits among different transformers but will generally be approximately $\frac{1}{2}\%$ to $1\frac{1}{2}\%$ of normal voltage of the winding at normal frequency.

The end terminals of the winding must be used, not taps, so that current will circulate through the total winding. The amount of current may be controlled by a rheostat in series with high-voltage winding.

This method of drying out is superficial and slow and should only be used with small transformers, and then only when local conditions prohibit the use of the other methods.

(b) **By External Heat.**—The transformer may be placed in its own tank without oil. Externally heated air is blown into the tank at the bottom through the main oil valve. A small blower or fan should be used to get the proper circulation. It is necessary to force as much of the heated air as possible up through the ducts in the transformer windings. To accomplish this, baffles should be placed between the core and the case, closing off as much of the space as possible.

The best way to obtain the heated air is by blowing the air through grid resistors. The resistors should be placed in a fire-proof box. The temperature limits are the same as for method (a). The temperature of the air entering from the grids should not exceed 125°C . Measure the temperature of the windings by resistance measurements frequently to make sure that the transformer is not overheated.

The heat may also be obtained by direct combustion, but it is essential that none of the products of combustion be allowed to enter the transformer case. Heating the air by combustion is not recommended except where electric current is not available.

If for any reason it is not expedient to place the transformer in its own tank, it may be placed in a wooden box with holes near the bottom and top for circulating warm air. The same precautions as given for drying in its own tank should be taken to see that the air is forced to circulate through the oil ducts in the insulation.

It is essential that every precaution be taken to prevent fire when drying out by this method. The set up must be watched very carefully during the entire drying. If the blower should stop, the grid current should be turned off at once to prevent overheating.

(c) **Internal and External Heat.**—This is a combination of methods (a) and (b). The transformer should be placed in its own tank, if possible, and all precautions taken as outlined under method (b). The current circulated in the windings should, of course, be less than when method (a) alone is used.

(d) **By Heating in Oil.**—For this method the transformer is submerged in oil and the heat is generated similar to method (a). The moisture is driven from the coils and insulation into the oil, and is removed from the oil by evaporation into the air or filtering, or by both evaporation and filtering.

The temperature of the windings should be maintained at 80° to 90° C. as determined by resistance measurement. The oil should be maintained at as high a temperature as possible to keep a safe temperature in the windings. To bring the oil up to a temperature sufficient to evaporate the moisture into the air, it will be necessary to reduce or cut off the water in a water-cooled transformer, and to limit the radiation in a self-cooled transformer. The radiation may be limited by lagging the tank, or a portion of it, with some suitable heat insulating material. If external radiators are used, the oil circulation in the radiators should be prevented by closing the radiator valves or by lowering the oil level below the top radiator connections.

It is essential that plenty of ventilation be provided in the air space above the oil, in order that the moisture may evaporate from the oil. The man hole covers may be raised and, if necessary, forced ventilation used. If the ventilation is not sufficient, moisture will condense on the cover and drip into the oil. If this occurs, the ventilation should be increased or the temperature of the oil reduced.

Filtering the oil will aid materially in removing the moisture, and hasten the process of drying.

The rate of evaporation depends on the temperature of the oil and the ventilation, but special care should be used to see that the windings and insulation, which are at a higher temperature than the oil, do not reach a dangerous temperature.

Remember when taking megger readings that the megohm resistance is a function not only of the dryness but of the size of the transformer and of the arrangement of the windings as well.

Most operating companies consider a transformer dry when the megger readings are constant over a period of 24 hours.

CHAPTER 17

OHM'S LAW

(Practical Applications)

General.—When a current flows in an electric circuit the magnitude of the current is determined by the electromotive force in the circuit and the resistance of the circuit, the resistance being dependent on the material, cross-section and length of the conductor.

The relationship between an unvarying electric *current* (I), *electromotive force* (E) and resistance (R) is expressed by Ohm's law, and is written:

$$I = \frac{E}{R} \quad (1)$$

or $E = IR \quad (2)$

and $R = \frac{E}{I} \quad (3)$

Where **I** = current flow in amperes.

E = electromotive force in volts.

R = resistance in ohms.

Ques. A direct current circuit has a resistance of 5 ohms. If a voltmeter connected across its terminal reads 10 volts, how much current will flow?

Ans. From Ohm's law the current $I = \frac{E}{R} = \frac{10}{5} = 2$ amperes

Ques. If the resistance of a circuit is 25 ohms, what voltage is necessary for a current flow of 4 amperes?

Ans. From Ohm's law the voltage,
 $E = I \times R = 4 \times 25 = 100$ volts.

Ques. If the potential across a circuit and the current flowing through it be measured as 40 volts and 5 amperes respectively, what is the resistance?

Ans. From Ohm's law, the resistance

$$R = \frac{E}{I} = \frac{40}{5} = 8 \text{ ohms.}$$

Series Circuits

A series circuit may be defined as one in which the resistances are connected in a continuous run (i.e., connected end to end) as shown in fig. 1. It is evident that since the circuit has no branches, the same current flows in each resistance. The total potential across the whole circuit, equals the potential drop due to each individual resistance, or

$$\begin{aligned} E_1 &= I R_1 \\ E_2 &= I R_2 \\ E_3 &= I R_3 \end{aligned} \tag{4}$$

Since

$$E = E_1 + E_2 + E_3 \tag{5}$$

and

$$R = R_1 + R_2 + R_3 \quad (6)$$

the equation for the total potential of the circuit is

$$E = IR_1 + IR_2 + IR_3 = I(R_1 + R_2 + R_3) \quad (7)$$

and

$$I = \frac{E}{R_1 + R_2 + R_3} = \frac{E}{R} \quad (8)$$

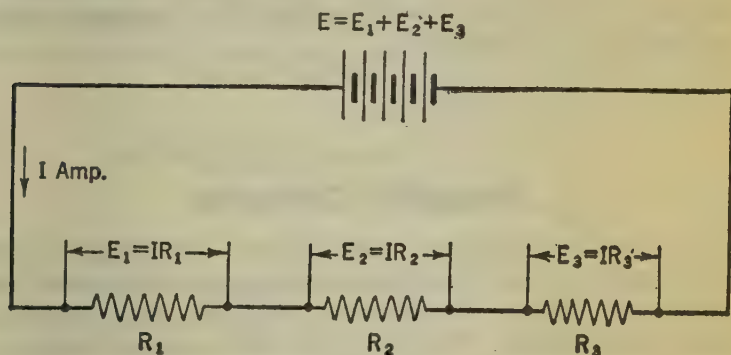


Fig. 1—Resistances in series.

Ques. If the individual resistances fig. 1 are 5, 10 and 15 ohms respectively, what potential must the battery supply to force a current of 0.5 amperes through the circuit.

Ans. The total resistance.

$$R = 5 + 10 + 15 = 30 \text{ ohms}$$

Hence the total voltage

$$E = 0.5 \times 30 = 15 \text{ volts.}$$

As a check we may calculate the voltage drops across each part; thus:

$$E_1 = 0.5 \times 5 = 2.5 \text{ volts}$$

$$E_2 = 0.5 \times 10 = 5.0 \text{ volts}$$

$$E_3 = 0.5 \times 15 = 7.5 \text{ volts}$$

and

$$E = E_1 + E_2 + E_3 = 2.5 + 5.0 + 7.5 = 15 \text{ volts, as before.}$$

Ques. In order to determine the voltage of a d.c. source, three resistance units of 10, 15 and 30 ohms are connected in series. If the current through the circuit be 2 amperes, what is the potential of the source?

$$\begin{aligned} \text{Ans. } E &= I(R_1 + R_2 + R_3) = 2(10 + 15 + 30) \\ &= 2 \times 55 \text{ or } 110 \text{ volts.} \end{aligned}$$

Parallel Circuits

In a parallel (sometimes called divided) *circuit*, such as that shown in fig. 2, the voltage across the group is the same, and the current flowing through each resistance varies inversely with the value of it. The sum of all the currents, however, is equal to the main current leaving the battery. Thus,

$$E = I_1 R_1 = I_2 R_2 = I_3 R_3$$

and

$$I = I_1 + I_2 + I_3$$

When Ohm's law is applied to the individual resistances, the following is obtained:

$$I_1 = \frac{E}{R_1}; I_2 = \frac{E}{R_2} \text{ and } I_3 = \frac{E}{R_3}$$

Hence

$$I = \frac{E}{R_1} + \frac{E}{R_2} + \frac{E}{R_3}$$

or

$$I = E \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right)$$

and since $I = \frac{E}{R}$, the equivalent resistances of the several resistances connected in parallel is

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \quad (9)$$

Thus, we have found that any number of resistances in parallel can be replaced by an equivalent resistance whose value is equal to the reciprocal of the sum of the reciprocals of the individual units.

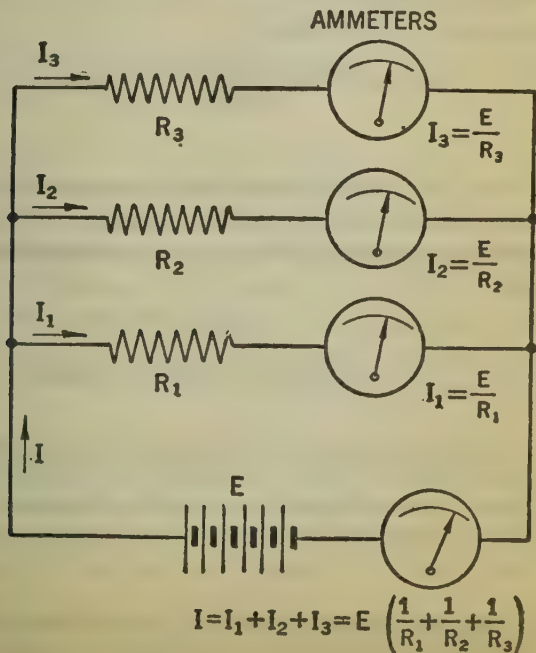


Fig. 2—Parallel resistance circuit.

The value $1/R$ is expressed as the *conductance of the circuit*, its unit is *mho*, and is usually expressed by g or G .

It is written
$$g = \frac{1}{R} \quad (10)$$

When there are only two resistances connected in parallel

$$R = \frac{R_1 R_2}{R_1 + R_2} \text{ ohms} \quad (11)$$

If there be three resistances connected in parallel

$$R = \frac{R_1 R_2 R_3}{R_1 R_2 + R_1 R_3 + R_2 R_3} \text{ ohms} \quad (12)$$

The conductance of this circuit is

$$g = \frac{1}{R} = \frac{R_1 R_2 + R_1 R_3 + R_2 R_3}{R_1 R_2 R_3} \text{ mhos} \quad (13)$$

Ques. A wire of 2 ohms resistance is connected in series with a group of three wires in parallel, which are of 4, 5 and 20 ohms resistance respectively. What is the equivalent resistance of the circuit?

Ans. The conductance of the parallel branch—

$$\frac{1}{R} = \frac{1}{4} + \frac{1}{5} + \frac{1}{20} = 0.25 + 0.20 + 0.05 = 0.5 \text{ mho}$$

$$R = \frac{1}{0.5} = 2 \text{ ohms (equivalent resistance of parallel branch)}$$

As the circuit is now reduced to two series resistances each of 2 ohms, equivalent resistance of circuit, $= 2 + 2$ or 4 ohms.

Ques. A group of wires in parallel of 2 and 6 ohms resistance respectively, is connected in series with another group of three

wires in parallel with 1, 3 and 6 ohms resistance, respectively. If the conductor by means of which the two groups are connected in series, has a resistance of 1.5 ohms, what is the equivalent resistance of the system?

Ans. Replace the 2 and 6 ohms resistance by a resistance R_1 , where

$$\frac{1}{R_1} = \frac{1}{2} + \frac{1}{6} = 0.5 + 0.167 = 0.667 \text{ mho}$$

$$\text{and } R_1 = 1.5 \text{ ohms}$$

Replace the group of three resistances by R_2 , where

$$\frac{1}{R_2} = \frac{1}{1} + \frac{1}{3} + \frac{1}{6} = 1.000 + 0.333 + 0.167 = 1.5 \text{ mhos.}$$

$$R_2 = \frac{1}{1.5} = 0.667 \text{ ohm}$$

The circuit is now reduced to three series resistances the values of which are 1.5, 1.5 and 0.667 ohms. Their combined values are:

$$R_{total} = R + R_1 + R_2 = 1.5 + 1.5 + 0.667 = 3.667 \text{ or } 3\frac{2}{3} \text{ ohms. Ans.}$$

Units of Area and Resistance

Circular mil.—The *circular mil* is the unit of cross-section used in the American wire gauge. The term mil means *one-thousandth* of an inch (0.001 inch).

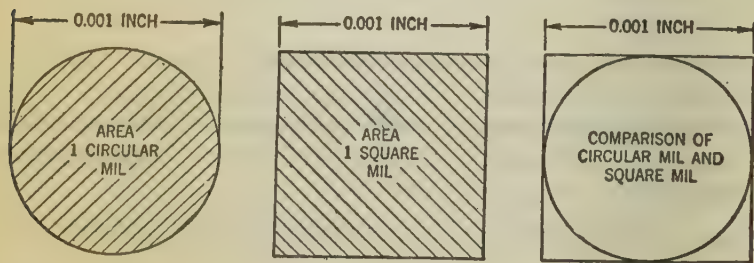
It is the area of a *circular wire* having a diameter of one mil 0.001 inch, as shown in fig. 3.

The *circular milage* of any solid cylindrical wire is equal to its diameter, expressed in mils, *squared*. Thus, for example, the area in circular mils (written *C.M.* or *cir. mil.*) of a wire having a diameter of say $\frac{3}{8}$ inch equals $375 \times 375 = 375^2 = 140,625$ C.M.

The *diameter* in mils of a solid circular wire is equal to the *square root* of its circular milage.

Assuming a conductor has an area of say 500,000 C.M. its diameter in mils $= \sqrt{500,000} = 707$ or 0.707 inch (approximately.)

The area in square inches of a wire $= \frac{\pi D^2}{4} = 0.7854 D^2$ thus, the area in square inches of a circular mil $= 0.7854 \times 0.001^2 = 0.0000007854$ sq. in.



Figs. 3 to 5—Enlarged view of circular mil and square mil; fig. 5, indicates relative size of the two units.

Square mil.—The square mil is the area of a square each side of which is one mil (0.001 inch). Hence, the area of a square mil is $0.001^2 = 0.000001$ sq. in.

Relation between circular mils and square mils.—With reference to the previous definitions of the circular mil and square mil, it is obvious that in order to convert a unit of circular area

into its equivalent units in square mils, the circular mil should be multiplied by $\pi/4$ or 0.7854 and conversely to convert a unit area of square mils into its equivalent area in circular mils, the square mil should be divided by $\pi/4$ or 0.7854.

The above relations may be written as follows:

$$\text{square mils} = \text{circular mils} \times 0.7854.$$

$$\text{circular mils} = \frac{\text{square mils}}{0.7854}$$

Thus, any circular conductor may easily be converted into a rectangular conductor (bus bar for example) containing the same area, or current carrying capacity.

Ques. If number 000 wire AWG (American wire gauge) has an area of 167,800 C.M. what is its diameter?

Ans. The diameter in mils $= \sqrt{167,800} = 409.6 = 0.4096$ in.

Ques. If number 10 wire (AWG) has a diameter of 101.9 mils, what is its circular milage?

Ans. C.M. $= 101.9^2 = 10,383.61$.

Ques. A certain switchboard arrangement, fig. 6 necessitates a conversion from a circular conductor to a rectangular bus bar having the same area. If the diameter of the solid conductor is measured as 0.846 in. calculate:

- (a) Width of an equivalent bus bar if the thickness of the bar be $\frac{1}{4}$ in.
- (b) Its area in circular mils.
- (c) Current carrying capacity if one square inch of copper carries 1,000 amperes?

Ans. Area in square inch of the circular conductor

$$A = 0.7854 \times D^2 = 0.7854 \times 0.846^2 = 0.562 \text{ sq. in.}$$

Area in square inch of the bus bar

$$A' = 0.25 \times W$$

and since

$$A' = A = 0.562 = 0.25 W$$

(a)

$$W = \frac{0.562}{0.25} = 2.248 \text{ say } 2\frac{1}{4} \text{ inches.}$$

(b) Area in C.M. of conductor = $846^2 = 715,716$

(c) Current carrying capacity = $0.562 \times 1000 = 562 \text{ amp.}$

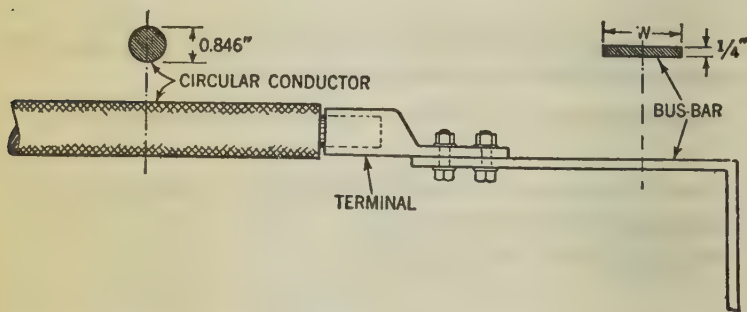


Fig. 6—Method of connection between a circular and rectangular conductor.

Ques. What is the area in square and circular mils of a rectangular bar measuring 2 inches by $\frac{3}{8}$ inch?

Ans. The area in square mils is $2000 \times 375 = 750,000$

The area in circular mils:

$$= \frac{750,000}{0.7854} = 954,900$$

Ques. A certain 115 volt, 100 horse power D.C. motor has an efficiency of 90% and takes a starting current 150% times the full load current. Determine:

- Size of fuses
- Copper requirements of switch. (Assume one square inch of copper carries 1,000 amperes.)

Ans. Motor current

$$I_m = \frac{HP \times 746}{E \times \text{efficiency}} = \frac{100 \times 746}{115 \times 0.9} = 721 \text{ amperes (approximately)}$$

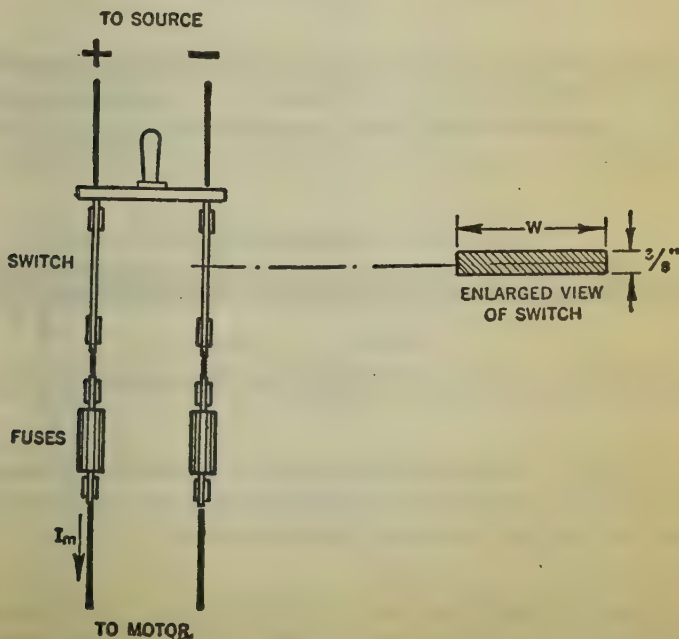


Fig. 7—Layout showing how the size of a double pole single throw switch may be determined.

- (a) The amperage of the fuses is therefore $721 \times 1.5 = 1,081.5$ say 1,100 amperes.
- (b) As the motor takes a current of 721 amperes the copper of each switch blade must be

$$\frac{721}{1,000} \text{ or } 0.721 \text{ square inch.}$$

Thus, if $\frac{3}{8}$ inch bus copper be used, its width

$$W = \frac{0.721}{0.375} = 1.92 \text{ inches, say 2 inches.}$$

Circular mil-foot.—The mil-foot is a unit circular conductor *one foot in length* and *one mil in diameter*. The resistance of such a unit of copper has been found experimentally to be 10.37 *ohms* at 20° C.

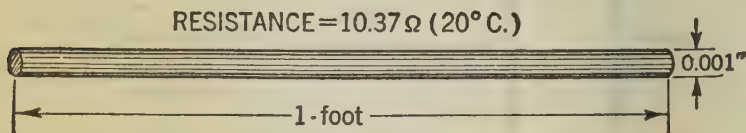


Fig. 8—Illustrating dimensions and resistance of a circular mil-foot of copper.

This value is important and should be remembered because from this the resistance of copper conductors of any cross-section and length may easily be calculated.

Resistance determination.—The resistance of a wire depends directly upon its length and inversely upon its cross-section. Thus, *if the resistance of a mil-foot of the wire (given in ohms) be*

multiplied by the total length in feet and divided by its cross-section in circular mils, the result will be the total resistance of the wire in ohms.

This is expressed as

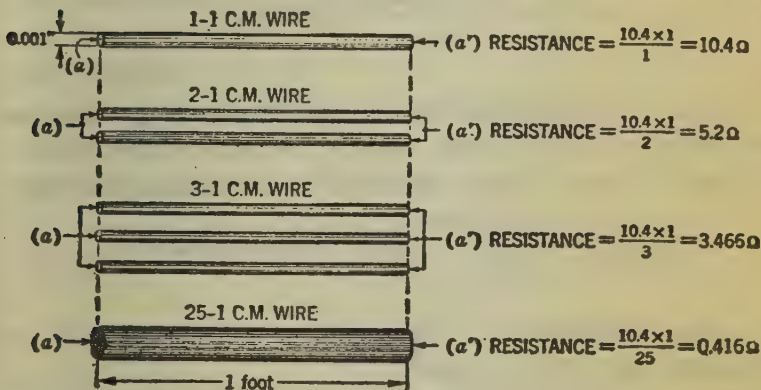
$$R = \rho \frac{L}{A} \quad (14)$$

Where R = resistance in ohms

ρ = resistance of one mil-foot (10.4 for copper)

L = length in feet

A = area in circular mils



Figs. 9 to 12—Illustrating how the resistance decreases with an increase of the area through which the current flows. Fig. 9 indicates the ohmic resistance between terminals a - a' when one circular mil-foot be employed; figs. 10 and 11, indicate how the resistance between terminals a - a' decreases when the same conductors are connected in parallel; fig. 12, shows resistance between terminals a - a' when 25 one circular mil conductors are bundled together. The resistance in this latter case is only 1/25th of that of the single conductor. Thus, any wire may be thought of as composed of a bundle of wires, each one circular mil in cross-section bound together. The number of circular mils in a given wire is then the number of circular mil wires required to make up the cross-section in question.

Ques. What is resistance of a copper wire 1,000 ft. in length when its cross-section is 50,000 circular mils?

Ans. Using formula (14) we obtain:

$$R = \rho \frac{L}{A} = \frac{10.4 \times 1,000}{50,000} = 0.208 \text{ ohm.}$$

Ques. Suppose it be desired to have a copper wire of 0.5 ohm resistance and 2,000 ft. in length, what must be its cross-section?

Ans. We have

$$A = \rho \frac{L}{R} = \frac{10.4 \times 2,000}{0.5} = 41,600 \text{ C.M.}$$

Ques. If the resistance of a copper wire of $\frac{1}{8}$ in. diameter be measured as 0.125 ohm, what is the length of the wire?

Ans. If formula (14) be solved with respect to (L) we obtain:

$$L = \frac{RA}{\rho} = \frac{0.125 \times 125^2}{10.4} = 188 \text{ ft. (approximately).}$$

Ques. Determine the resistance of a wire 0.162 in. in diameter and 500 ft. in length.

Ans.

$$R = \frac{10.4 \times 500}{162^2} = 0.198 \text{ ohm.}$$

Ques. A wire 1,000 ft. in length and 0.2 in. in diameter has a resistance of 0.26 ohm. Calculate the resistance of a wire of the same material 500 ft. in length and 0.04 in. in diameter.

Ans. The resistance per mil-foot of both wires

$$\rho = \frac{RA}{L} = \frac{0.26 \times 200^2}{1,000} = 10.4$$

The resistance of the 500 ft. wire is

$$R = \frac{10.4 \times 500}{40^2} = 3.25 \text{ ohms.}$$

Ques. A copper wire 10 miles in length has a diameter of 0.25 in.

Calculate:

(a) Diameter of the wire in mils.

(b) Area of wire in circular mils.

(c) Weight in pounds.

(d) Resistance at 20° C.

(Assume weight in pounds per cubic inch = 0.321)

Ans.

(a) Diameter in mils = $1,000 \times 0.25 = 250$

(b) Area in C.M. = $250^2 = 62,500$ C.M.

(c) Cross-sectional area = $0.7854 \times D^2 = 0.7854 \times 0.25^2 = 0.0491$ sq. in.

Length of wire = $5,280 \times 10 \times 12 = 633,600$
inches

Weight of wire = $0.0491 \times 633,600 \times 0.321 = 9,986.23$, say 10,000 lbs.

(d) $R = \frac{\rho \times L}{A} = \frac{10.37 \times 5,280 \times 10}{62,500} = 8.76$ ohms.

Relations between circular mils and square millimeters.—

In many European and South American countries, the cross-section area of wires is calculated in *square millimeters* instead of

in *circular mils*. The relations between the two units may be derived as follows:

If it be kept in mind that one inch equals 25.4 millimeters, the area in square millimeters of a circular conductor one inch in diameter is:

$$\frac{25.4^2 \times \pi}{4} = 506.707 \text{ sq. mm.}$$

The area in C.M. of an equal conductor is
 $1,000^2 = 1,000,000 \text{ C.M.}$

It follows that

$$1 \text{ sq. mm.} = \frac{1,000,000}{506.707} = 1,973.5 \text{ circular mils}$$

and $1 \text{ C.M.} = 0.000506707 \text{ square millimeters}$

Ques. A circular conductor has a diameter of 100 mils. What is its area in square millimeters?

Ans.

$$\text{Diameter} = 0.1 \text{ inch} = 2.54 \text{ mm.}$$

$$\text{Area in sq. mm.} = \frac{\pi}{4} \times 2.54^2 = 5.07$$

Ques. What is the resistance of a copper conductor 5 kilometers in length, when the diameter of the wire is 3 millimeters? (The resistance of a copper wire 1 square millimeter in cross-section and 1 meter in length equals 0.0175 ohm.)

Ans.

$$R = \frac{\rho \times L}{A} = \frac{0.0175 \times 5,000}{\frac{\pi}{4} \times 3^2} = 12.38 \text{ ohms.}$$

Ques. What is the resistance of 1 kilometer of copper wire having a cross-section of 6 sq. mm.? What is the equivalent circular mileage of the wire?

Ans.

$$R = \rho \frac{L}{A} = \frac{0.0175 \times 1,000}{6} = 2.917 \text{ ohms.}$$

Equivalent circular mileage $1,973.5 \times 6 = 11,841 \text{ C.M.}$

Ques. A copper conductor 2 kilometers in length has a cross-section area of 6 square millimeters. What is its resistance in ohms, if the resistance of a copper conductor one meter in length with a cross-section of one sq. mm. equals 0.0175 ohm?

Ans.

$$R = \rho \frac{L}{A} = \frac{0.0175 \times 2,000}{6} = 5.834 \text{ ohms}$$

Ques. What is the resistance per circular mil-foot when the resistance of a wire 6,562 ft. in length with an area of 11,841 C.M. is 5.834 ohms?

Ans.

$$\rho = \frac{RA}{L} = \frac{5.834 \times 11,841}{6,562} = 10.53 \text{ ohms.}$$

American Wire Gauge (B. & S.).—The *American wire gauge* was devised by J. R. Brown, one of the founders of the Brown & Sharpe Manufacturing Co., in 1857. It speedily superseded the Birmingham wire gauge in this country, which was then in general use. It is perhaps more generally known by the name Brown & Sharpe Gauge, but this name is not the one preferred by the Brown & Sharpe Co. In their catalogues they regularly refer to the gauge as the American Standard Wire Gauge. The word Standard is probably not a good one to retain in the name of this

gauge, since it is not the standard gauge for *all* metals in the United States; and, further, since it is not a legalized gauge, as are the (British) *Standard Wire Gauge* and the United States *Standard Sheet-Metal Gauge*. The abbreviation for the name of this gauge has usually been written A. W. G. The American wire gauge is now used for more metals than any other in this country, and is practically the only gauge used for copper and aluminum wire, and in general for wire used in electrical work. It is the only wire gauge now in use whose successive sizes are determined by a simple mathematical law.

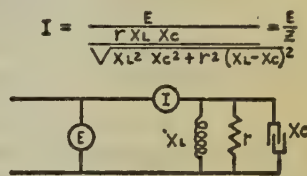
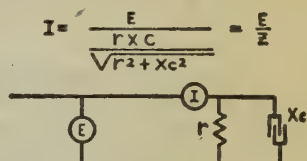
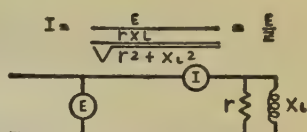
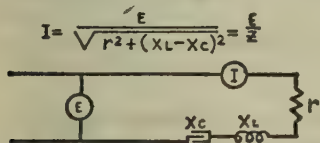
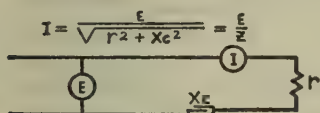
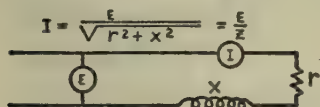
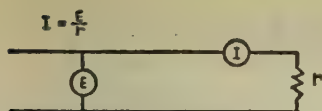
The American wire gauge has the property, in common with a number of other gauges, that its sizes represent approximately the successive steps in the process of wire drawing. Also, like many other gauges, its numbers are retrogressive, a larger number denoting a smaller wire, corresponding to the operations of drawing. No. 0000 wire is the largest size wire of the gauge. Conductors larger than 0000 are practically always stranded and their cross-sections are specified in circular mils.

The gauge is formed by the specification of two diameters and the law that a given number of intermediate diameters are formed by geometrical progression. Thus, the diameter of No. 0000 is defined as 0.4600 in. and of No. 36 as 0.0050 in. There are 38 sizes between these two; hence the ratio of any diameter to the diameter of the next great number

$$= \sqrt[39]{\frac{.4600}{.0050}} = \sqrt[39]{92} = 1.122\ 932\ 2$$

The square of this ratio = 1.2610. The sixth power of the ratio, i.e., the ratio of any diameter to the diameter of the sixth greater number = 2.0050. The fact that this ratio is so nearly 2 is the basis of numerous useful relations.

Formula For Determining Alternating Current In Alternating Current Circuits



Figs. 13 to 19—Illustrating fundamental forms of alternating current circuits, and method of determining current values when pressure in volts and impedance in ohms are known.

In the foregoing formulae:

r = Resistance in Ohms

x_L = Inductive reactance in Ohms = $2\pi fL$

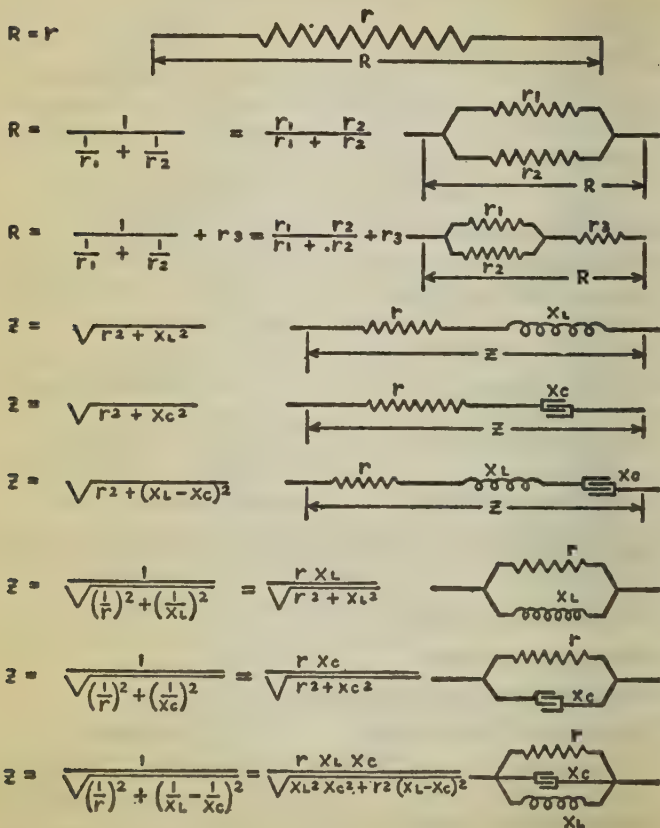
x_c = Condensive Reactance in Ohms = $\frac{1}{2\pi fC}$ $\left\{ \begin{array}{l} f = \text{frequency} \\ L = \text{ind. in Henrys} \\ C = \text{capacity in Farads} \end{array} \right.$

Z = Impedance in Ohms

I = Current in Amperes

E = Pressure in Volts

Formula For Combining Resistance And Reactance



Figs. 20 to 28—Method of impedance determination in alternating current circuits when resistance, inductive reactance and condensive reactance in ohms are known.

In the foregoing formulae:

r = Resistance in Ohms

X_L = Inductive reactance in Ohms = $2\pi fL$

X_C = Condensive Reactance in Ohms = $\frac{1}{2\pi fC}$ $\left\{ \begin{array}{l} f = \text{frequency} \\ L = \text{ind. in Henrys} \\ C = \text{capacity in Farads} \end{array} \right.$

Z = Impedance in Ohms

I = Current in Amperes

E = Pressure in Volts

Ques. A coil contains a resistance of 10 ohms and in series with it an inductance of 0.1 henry. If the frequency of the source be 60 cycles, find the voltage necessary to cause a current of 2 amperes to flow through the circuit.

Ans. With reference to previously derived formula

$$E_R = IR = 2 \times 10 = 20 \text{ volts}$$

$$X_L = 2\pi fL = 2\pi 60 \times 0.1 = 37.7 \text{ ohms}$$

$$E_L = IX_L = 2 \times 37.7 = 75.4 \text{ volts}$$

The applied voltage must therefore be

$$E = \sqrt{E_R^2 + E_L^2} = \sqrt{20^2 + 75.4^2} = 78 \text{ volts.}$$

Ques. A coil that has a negligible resistance takes 3 amperes when connected to a 180 volt, 60 cycle supply. Determine the inductance of the coil.

Ans.

$$X_L = \frac{E}{I} = \frac{180}{3} = 60 \text{ ohms}$$

and

$$X_L = 2\pi fL$$

from which
$$L = \frac{60}{2\pi \times 60} = 0.159 \text{ henry.}$$

Ques. An alternating current of 15 amperes having a frequency of 60 cycles is impressed on a circuit containing a resistance of 5 ohms and an inductance of 15 milli-henries. Find the impressed voltage.

Ans.

$$X_L = 2\pi fL = 2\pi \times 60 \times 0.015 = 5.65 \text{ ohms}$$

$$Z = \sqrt{R^2 + X_L^2} = \sqrt{5^2 + 5.65^2} = 7.54 \text{ ohms}$$

$$E = IZ = 15 \times 7.54 = 113.1 \text{ volts.}$$

Ques. A coil contains 5 ohms resistance and 0.04 henry inductance. The voltage and frequency of the source is 100 and 60 respectively. Find (a) the impedance of the coil; (b) the current through the coil; (c) the voltage drop across the inductance; (d) the voltage drop across the resistance.

Ans.

$$X_L = 2\pi fL = 2 \times 3.14 \times 60 \times 0.04 = 15 \text{ ohms.}$$

$$(a) \quad Z = \sqrt{5^2 + 15^2} = \sqrt{250} = 15.8 \text{ ohms.}$$

$$(b) \quad I = \frac{E}{Z} = \frac{100}{\sqrt{5^2 + 15^2}} = 6.3 \text{ amperes.}$$

$$(c) \quad E_L = IX_L = 6.3 \times 15 = 94.5 \text{ volts.}$$

$$(d) \quad E_R = IR = 6.3 \times 5 = 31.5 \text{ volts.}$$

Ques. An alternating current circuit contains 10 ohms resistance in series with a capacitance of 40 microfarads. The voltage and frequency of the source is 120 and 60 respectively; find:

- (a) The current in the circuit
- (b) the voltage drop across the resistance
- (c) The voltage drop across the capacitance
- (d) the power factor
- (e) the power loss

Ans.

$$X_c = \frac{1}{2\pi fC} = \frac{1}{2 \times \pi \times 60 \times 0.00004} = 66.3 \text{ ohms}$$

$$Z = \sqrt{10^2 + 66.3^2} = 67 \text{ ohms}$$

- (a) $I = \frac{E}{Z} = \frac{120}{67} = 1.8 \text{ amperes.}$
- (b) $E_R = IR = 1.8 \times 10 = 18 \text{ volts.}$
- (c) $E_c = IX_c = 1.8 \times 66.3 = 119.3 \text{ volts.}$
- (d) $\cos \phi = \frac{R}{Z} = \frac{10}{67} = 0.15 \text{ or } 15\%.$
- (e) $P = E \times I \times \cos \phi = 120 \times 1.8 \times 0.15 = 32 \text{ watts. (Approx.)}$

Ques. A coil of 3 ohms resistance and 20 milli-henries inductance is connected in series with a condenser of 400 microfarads capacitance. If the voltage and frequency are 120 and 60 respectively, find:

- (a) Impedance of the combination
- (b) Current that flows
- (c) Power loss
- (d) Power factor

Ans.

$$X_L = 2\pi fL = 2\pi \times 60 \times 0.020 = 7.54 \text{ ohms}$$

$$X_C = \frac{1}{2\pi \times 60 \times 0.0004} = 6.63 \text{ ohms}$$

$$(a) \quad Z = \sqrt{R^2 + (X_L - X_C)^2} = \sqrt{3^2 + (7.54 - 6.63)^2} \\ = 3.13 \text{ ohms.}$$

$$(b) \quad I = \frac{E}{Z} = \frac{120}{3.13} = 38.3 \text{ amperes.}$$

$$(c) \quad P = I^2 R = 38.3^2 \times 3 = 4,400 \text{ watts.}$$

$$(d) \quad \cos \phi = \frac{R}{Z} = \frac{3}{3.13} = 0.958 \text{ or } 96\% \text{ (approximately).}$$

SECTION

2



**MOTOR
WINDINGS**

CHAPTER 18

Fundamentals of Commutation

General.—The subject of commutation is considered by many to be one of the most intricate in the science of electrical engineering. It involves a number of factors the relationship of which is difficult to establish experimentally, and equally difficult to analyze, except on a basis of approximation, by mathematical means. It is, therefore, impossible to attempt a detailed treatment of this subject in all its phases within the limits of this chapter.

Some of the elementary principles involved will be presented, however, in order to give an insight into the functions the brush is called upon to perform.

Relative Directions of Motion Flux and Current.—Consider first the method by which a current of electricity is generated. Assume the conductor, illustrated in fig. 1, to be moved downward past the poles of a magnet, cutting the lines of magnetic force. An electromotive force (voltage) will be induced in the conductor by this action. If the ends of the conductor are connected to some external circuit, such as the galvanometer (*G*) shown in the illustration, current will flow in the circuit so formed.

The direction of this *e.m.f.* and current will bear a definite relation to the direction of the magnetic flux and of the move-

ment of the conductor. As it passes the north pole of the magnet in the direction indicated by the vertical arrow, the direction of *e.m.f.* will be that indicated by the arrow on the conductor. As the conductor is carried on past the south pole of the magnet the direction of *e.m.f.* reverses, as will be indicated by a reversal of the galvanometer needle.

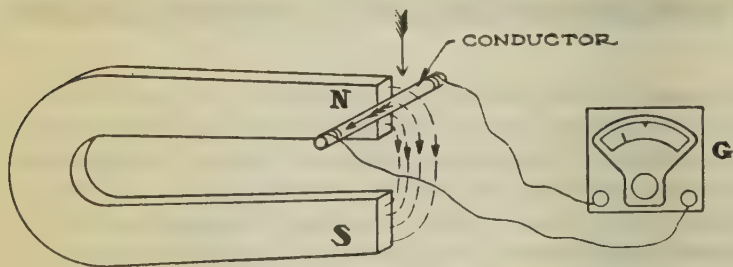


Fig. 1.—Illustrating electromagnetic induction.

Reversing the direction of either motion or flux reverses the direction of the *e.m.f.* generated in the conductor. Reversal of both motion and flux leaves the direction of the *e.m.f.* unchanged.

A simple method of determining the direction of the induced *e.m.f.* when the direction of magnetic flux and motion are known, is as follows: point the index finger of the right hand in the direction of the magnetic flux, assuming this direction to be from the *N* magnetic pole to the *S* pole through the intervening space; let the thumb be turned in the direction of motion; the second finger, extended perpendicular to the palm, will then indicate the direction of the induced *e.m.f.*

This is illustrated in fig. 2. By this rule the direction of either motion, magnetic flux or *e.m.f.* may be determined when two of these factors are known. This rule, for the right hand,

applies only to generated *e.m.f.* In the case of a motor the left hand should be used, and the extended second finger taken to indicate the direction of impressed *e.m.f.* or current.

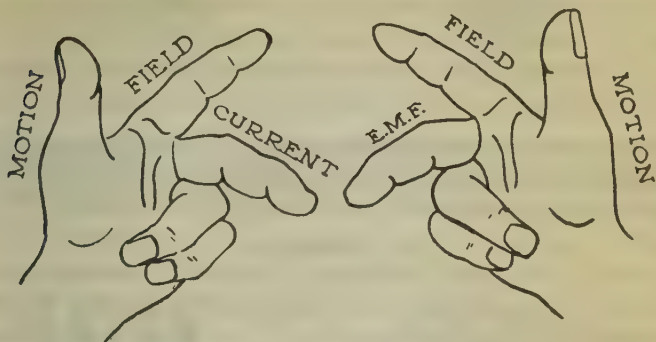


FIG. 2.—Illustrating hand rules for determining direction of induced *e.m.f.*'s. Left hand for motor and right hand for generator.

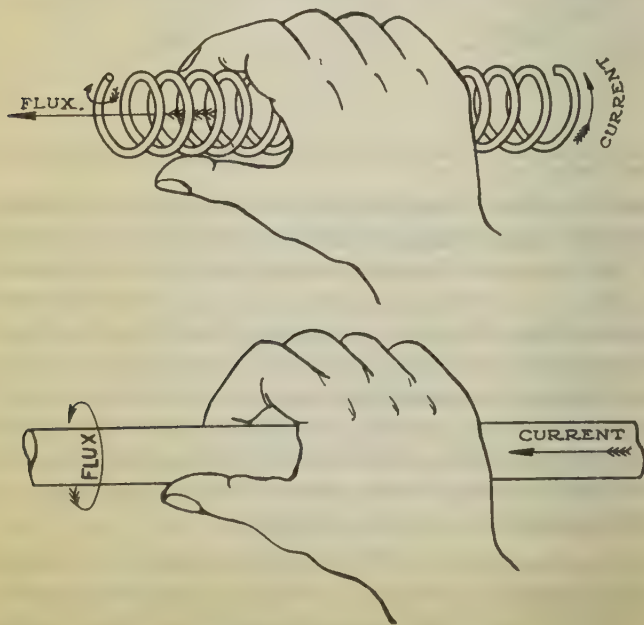
There is another fundamental relationship between electric current and magnetic flux, which it is well to fix in mind at this point. A conductor bearing current creates in the medium surrounding it a circular magnetic field, the direction of which is clockwise when the current is flowing away from the observer and counter-clockwise when the current is toward the observer.

This relation is indicated in figs. 3 and 4, which shows the cross section of two conductors and the surrounding fields. The plus sign and dot are the conventional symbols for indicating direction of current in the cross section of a conductor in the respective directions noted in the figure.

From the foregoing it will be readily apparent that the relation of the direction of magnetic flux through the interior of a coil of wire to that of the current flowing in the wire is as shown in fig. 5.



FIGS. 3 and 4.—Showing method of marking direction of current and flux in a conductor. When, as in fig. 3, the current in the conductor is in a direction away from the observer the surrounding flux is in a clockwise direction; on the other hand, when the current flow through the conductor (fig. 4) is toward the observer, the flux is in a counter-clockwise direction.



FIGS. 5 and 6.—Showing relation of flux and current in a conductor.

This relationship is indicated by grasping the coil in the right hand with the fingers pointing in the direction current is flowing in the wire. The extended thumb then indicates the direction of magnetic flux through the interior of the coil. This relationship, it may also be noted, is the same as the relative directions of travel and rotation in the case of a right hand screw. Similar analogies apply to the relative directions of current and surrounding magnetic flux in the case of a single conductor, fig. 6.

The strength of the *e.m.f.* generated in a conductor varies directly with the time rate at which it is cutting lines of magnetic force. It does not matter whether the motion is imparted to the conductor or to the magnetic flux. As long as there is relative motion between a conductor and lines of magnetic force, so that one cuts through the other, an *e.m.f.* will be generated in the conductor. If the pole of a magnet is thrust into the loop formed by bending a conductor until its ends meet, an *e.m.f.* will be generated momentarily and current will flow in the circuit of the conductor. When the magnet is withdrawn the *e.m.f.* and current will be in the opposite direction. From this it may be seen that changing the magnetic flux passing through a loop or coil of conducting material will produce the same effect as making the sides of the loop cut through a magnetic flux. In fact, the same action may be considered to take place.

When a magnetic flux is established through a loop, the lines of magnetic force completing the path of the magnetic circuit may be considered to spread outward cutting through the sides of the loop. When the magnetic flux is reduced, a certain number of lines may be considered to collapse and cut through the sides of the loop in the opposite direction.

Mechanical Generation of Electric Current.—Having seen how an *e.m.f.* may be generated in an electrical conductor by movement through or change in strength of a magnetic field, and current made to flow by making the electrical circuit complete, let us now see how this principle is applied to the generation of electric current by mechanical means.

Consider a coil of wire revolved between two magnetic poles of opposite polarity, as illustrated in fig. 7. For simplicity of drawing this has been illustrated as a single loop of wire, but the same principle will apply to a coil of any number of turns.

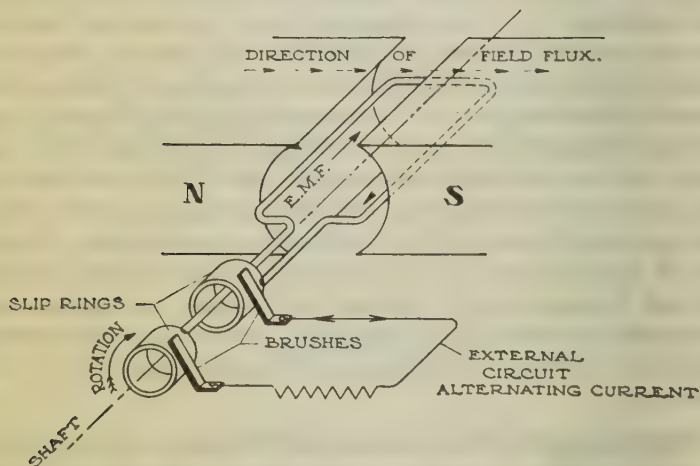


Fig. 7.—Illustrating generation of an alternating current.

From the foregoing it will be evident that an *e.m.f.* will be generated in the portions of this coil moving past the faces of the magnetic poles. As the movement of one side of the coil is up while the other is down and the direction of the magnetic flux is the same in both cases, the *e.m.f.* will be in opposite

directions on opposite sides of the coil, that is, it will be cumulative in effect as regards the entire coil.

If the ends of this coil are connected to slip rings on the shaft by which it is rotated and these, through brushes, to an external circuit, a current will flow in this external circuit corresponding to the *e.m.f.* in the coil. This current will have a certain direction during half the revolution of the coil, but during the other half revolution, the direction of motion of the sides of the coil with respect to the pole faces will be reversed with consequent reversal of *e.m.f.* and of the current in the external circuit. This produces what is known as an alternating current.

For many uses it is desirable that current should flow in but one direction. This is known as *direct current*, as distinguished from *alternating current*. To accomplish this it is necessary that the current generated in the revolving coil be commutated, that is, the connection of the ends of the coil to the external circuit must be reversed twice during each cycle through which it passes.

This result is accomplished by a commutator. A commutator is essentially a pole-changing switch consisting of two or more segments to which the ends of the coils are connected. It is mounted on the same element of the machine as the coils in which the *e.m.f.* is generated. Usually this is the revolving element of the machine and the unit, as a whole, is called the armature. The segments of the commutator are insulated from each other and from all other parts of the machine except the brushes which carry the current from the coils in which it is generated to the external circuit.

Fig. 8 illustrates the substitution of a commutator for the slip rings shown in fig. 7, so that current of constant direction is supplied to the external circuit. Bearing in mind that the

direction of current in a conductor passing a given pole face is always the same, it will be evident from a study of this figure that current will always flow away from the armature through one brush and back into the armature through the other.

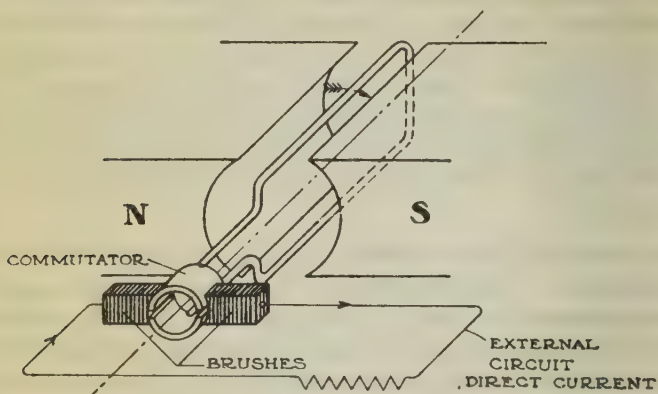


FIG. 8.—Illustrating generation of a direct current.

A machine for generating current by mechanical means is known as a *generator*. If used to generate *alternating current*, it is sometimes called an *alternator*. The part composed of the coils in which the *e.m.f.* is generated, the iron or steel core on which these coils are mounted and the commutator or slip rings to which these coils are connected is called the *armature*.

The part made up of the magnetic poles with their component magnetic circuit of iron or steel is called the field magnet or merely the field. In some small machines, known as magnetos, the field magnets are permanent magnets, but in most machines they are electro-magnets. The coils of wire on the field magnets, through which current is passed to establish a magnetic flux through the iron core, are called *field windings* or *field coils*.

A Simple Armature Winding and Commutator.—In the preliminary discussion of the generation of *e.m.f.* in an armature revolving in a magnetic field we have considered, for the sake of simplicity, only a single loop or coil of wire connected to a commutator of two segments. It would be necessary for such a coil to contain a great many turns or to be driven at a very high frequency in order to obtain the *e.m.f.* needed for practical application.

Furthermore, this *e.m.f.* and the current it would produce in the external circuit, while uniform in direction, would not be uniform in value, but would fluctuate between zero and a maximum. Reproduced in the form of a curve, its appearance would be similar to fig. 9, there being a wave for each magnetic pole as one side of the coil passes in its revolution.

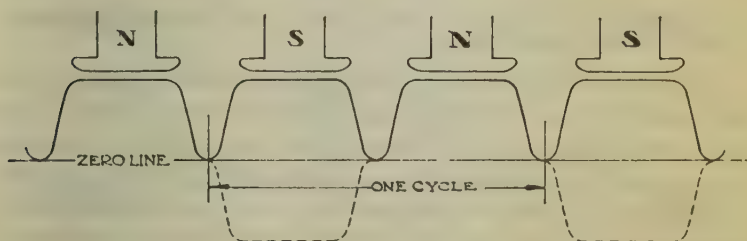


FIG. 9.—Illustrating form of *e.m.f.* curve generated in a single coil and rectified by a commutator. With slip rings, the curve would follow dotted line on alternate half-cycles.

If the armature were made up of two coils, 90 electrical degrees from each other and connected to a commutator of four segments, each coil would produce an *e.m.f.* wave form like that described previously and 90 electrical degrees apart. This condition, and the time relation between the *e.m.f.* waves in the two coils, are illustrated in fig. 10. It is evident that there may be momentary dips in the terminal voltage but that voltage never reaches zero, as it does with a single coil.

However, the circuits through the two coils being in multiple or parallel relation to each other, the maximum voltage at the terminals is no higher than that in the individual coils. Still further increase in the number of coils, with connections to the commutator segments so arranged as to place the coils in series with each other, increases both the value and the uniformity of the terminal voltage so that, with a multiplicity of coils, the terminal *e.m.f.* will have practically a constant value.

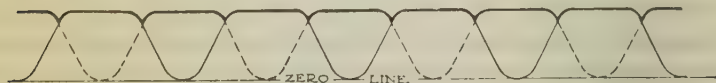


FIG. 10.—Illustrating *e.m.f.* curves for two-coil armature with four segment commutator. Heavy line indicates terminal voltage.

It is not advisable in this elementary analysis to enter into a discussion of the different types of armature winding. For the present purpose it will be sufficient to consider one simple type, an eight coil, two path, lap winding with an eight segment commutator. This is illustrated in fig. 11, the coils being shown of single turn and the brushes bearing on the interior of the commutator for the sake of simplicity in drawing.

The current generated by this armature returns from the external circuit through brush *N* and follows two paths through the armature to brush *P* where it again goes to the external circuit. These paths are *N-F-16-9-E-14-7-D-12-5-C-P* and *N-G-13-4-H-15-6-A-1-8-B-P*. Note that there are three coils in series in each path. The direction of the current in each armature conductor is indicated, the cross indicating that the current flows in a direction away from the observer and the dot indicating a direction toward the observer.

Conductors 5, 6, 7, 8, 13, 14, 15 and 16 are moving through the strong field under the poles and are generating the *e.m.f.* that is impressed on the external circuit. Conductors 1, 4, 9 and 12 are not cutting any flux except for a slight fringing field and that due to the distortion of the main field. This distortion will be discussed later. These conductors, however, are in series with those generating the *e.m.f.* and carry the same current.

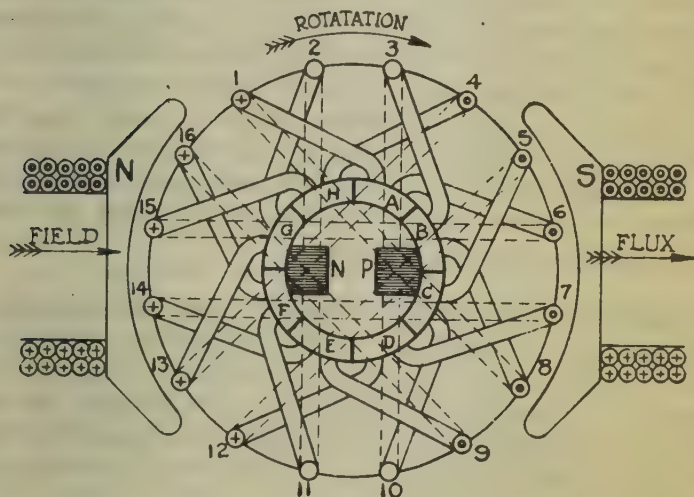


FIG. 11.—Diagram of simple armature winding.

Coils *B-3-10-C* and *G-2-11-F*, short circuited respectively by the brushes *P* and *N* are moving parallel to the main field and are not generating effective voltage nor carrying load current. They are the coils which are said to be undergoing commutation.

Consider coil *B-3-10-C*. When it was in the position now occupied by coil *A-1-8-B* current was flowing in it in the direction indicated by the order of the symbols *B-3-10-C*. When it comes into the position now occupied by the coil *D-12-5-C* current will be flowing in it in the direction *C-10-3-B*.

This reversal of current takes place while the commutator segments *B* and *C* are short-circuited by the brush *P* and is known as *commutation*. Immediately before and after the short-circuited period the coil is carrying full armature load current. Consequently, it is necessary that there be some means of suppressing the current flowing in the coil at the time it is short-circuited and reestablishing a current of like value in the opposite direction before the short circuit is broken.

If this is not done, the sudden rush of current, when the short-circuit is broken and load current forced through the coil, will cause an arc to be drawn between the brush and the commutator segment which is passing from under it. This phenomenon is known as *sparking*.

Inductance.—The reversal of current in the coil undergoing commutation is complicated by the property of inductance. Any coil of wire resists a change in the value of the current it is carrying, the amount of this resistance depending on the physical characteristics of the coil itself, the magnetic permeability of adjacent material and the time rate at which the current changes.

A clearer conception of this electrical characteristic, called *inductance*, may perhaps be obtained by considering its mechanical analogy, *inertia*. A mass, because of its inertia, resists either increase or decrease of its velocity and that resistance is proportional to the rate at which the velocity is changed. Likewise, an inductive electrical circuit resists any change in value of the current it is carrying.

This opposition takes the form of a counter *e.m.f.*, that is, a voltage having a direction which resists the change taking place. In the case of the commutating armature coil this counter *e.m.f.* is known as the reactance voltage. Methods used to overcome the reactance voltage and accomplish the reversal of current without sparking will be considered at a later point in this chapter.

Distortion of Magnetic Field.—Up to this point we have not considered the magnetic effect of the load current flowing in the armature conductors. It will be seen in fig. 11 that the armature conductors adjacent to the north pole of the field are carrying current away from the observer, and those near the south pole, toward the observer. The effect of these armature cross ampere-turns is to establish a magnetic flux at right angles to the main field, having a direction downward, as shown in this drawing, and varying in strength with the current flowing through the armature.

The resultant flux no longer flows directly from north to south pole with uniform distribution over the pole faces, but is distorted by an amount depending on the strength of the armature current. This results in lowering the flux density under the leading pole tips and increasing it under the trailing tips. This crowding of flux at the trailing tips is illustrated in fig. 12. This figure also indicates the increased “fringing” which occurs at the trailing tip as a result of the crowding of flux to that point.

For further simplicity in drawing, the commutator has been omitted in this figure and the brushes are shown bearing directly on the armature core. Due to the omission of the armature end windings the neutral point for the brushes in a drawing of this type is half way between the poles instead of at the center of the pole faces, as in practice, and as indicated in fig. 11.

With the field flux distorted by the armature current, a coil short-circuited by a brush in the mechanical neutral position is no longer free from *e.m.f.* This is because it is no longer moving parallel to the flux, but is cutting through it to some extent.

To overcome this condition, which would result in heavy current in the short-circuited coil, the brushes are shifted forward until commutation takes place at a time when the sides of the coil are moving parallel to resultant flux. In fact, the brushes should be shifted slightly beyond this electrically neutral point so that an *e.m.f.* will be generated to counteract the reactance voltage and aid in the reversal of the current in the coil.

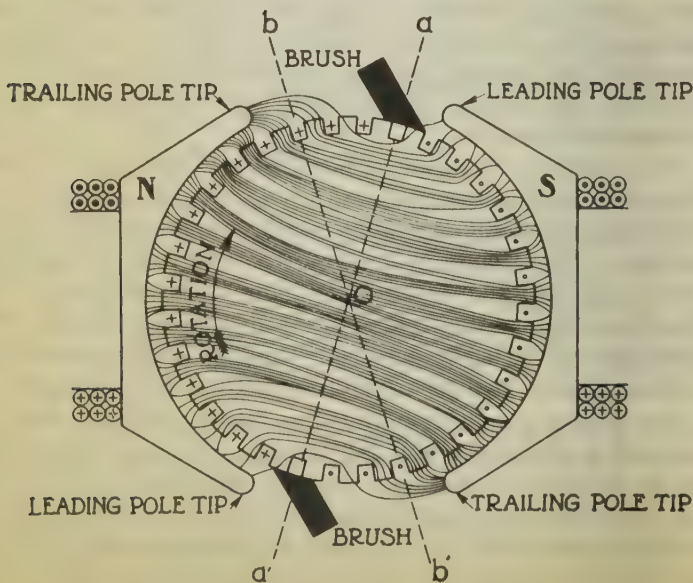


FIG. 12.—Diagram illustrating field distortion.

The angle by which the brushes are shifted ahead of the mechanical neutral position is called the angle of lead. This position is represented by the line aa' in the figure. If we draw line bb' at a corresponding angle behind the neutral position, the angle aob is called the double angle of lead. It will be noted that, as the brushes are shifted, the direction of current in the armature conductors is advanced at the same time.

As a rule the current is no longer balanced in all the conductors at the top and bottom of the armature, but those conductors included within the double angle of lead, aob and $a'ob'$ tend to establish a magnetic flux directly opposed to the main field. This magnetomotive force is called the *back ampere-turns*. The cross ampere-turns are now confined to the conductors within the angles aob' and $a'ob$. The strength and direction of the resultant flux may be indicated more clearly, perhaps, by means of the vector diagram in fig. 13. Here AB represents the strength and direction of the main field; BC , the back ampere-turns; CD , the cross ampere-turns, and AD , the resultant flux through the armature.

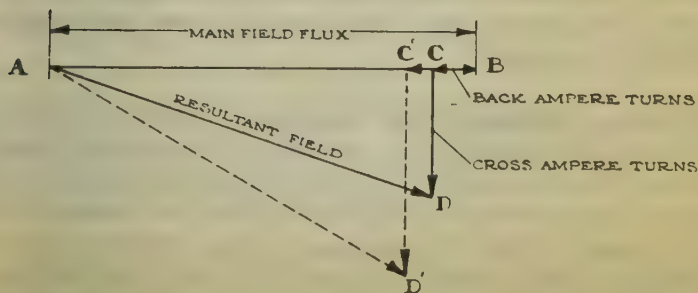


FIG. 13.—Illustrating vector diagram of main flux.

It is apparent that an increase in armature current will increase both BC and CD , as indicated in the figure by BC' and $C'D'$ and will result in a reduction, as well as a further distortion, of the resultant flux. For this reason a generator that is required to maintain constant voltage under all loads is provided with a compound field winding.

In addition to the shunt field winding, that is, the winding connected across the terminals of the armature, there are a number of turns on the field poles in series with the armature and carrying load current. These counteract the effect of the back ampere-turns on the armature and hold the magnetic flux, and consequently the voltage, up to its full value.

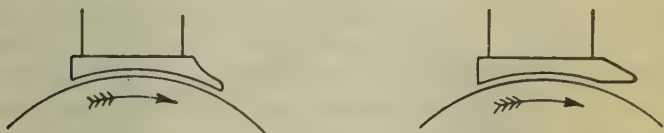
By putting on enough series turns the voltage of the generator may even be increased with increase in load. This is called over-compounding. However, compounding does not counteract the cross ampere turns and so does not prevent distortion of flux direction.

In a motor the flux distortion under load is against the direction of rotation and the brushes for best commutation should be shifted back of the mechanical neutral. Except for direction, however, the effect of load current on field strength and distortion is the same as those which have just been described for the case of a generator.

Methods of Reducing Field Distortion.—It will be apparent that where the distortion of the field is pronounced under changes of load, a machine will be very sensitive as to commutation and shifting of the brushes may be necessary for slight changes in load if sparking is to be avoided. Many methods have been devised to overcome this fault and maintain good commutation over a wide range of load. All have, as a primary purpose, the reduction of field distortion. A few of these methods will be discussed.

. One method is to use a long *air-gap* and a *stiff* field. The long air-gap produces a magnetic circuit of high reluctance, thereby minimizing the effect of the armature windings while the strong field winding brings the main flux up to the necessary value.

Saturation of the trailing pole tip by various means, such as giving it a special shape, fig. 14, is another means of preventing the shifting of the flux. If the pole tip is saturated the flux through it will increase very little, no matter what magnetomotive force is applied. Beveling the tip so that the flux encounters a longer air-gap as it tends to shift, is a modification of this method, illustrated in fig. 15.



FIGS. 14 and 15.—Fig. 14 illustrates pole shoe with thin trailing tip to limit shifting of field by saturation of tip. Fig. 15 shows pole shoe with face beveled at trailing tip to limit shifting of field by increasing reluctance of air gap.

A similar result is attained by the use of cast iron pole shoes. Cast iron has much lower magnetic permeability than steel, and will become saturated with a slight shifting of the flux and thus oppose further distortion. By using a thin shoe of cast iron at the pole face the total reluctance of the magnetic path through the field is not greatly increased.

Interpoles and Pole Face Winding.—Undoubtedly the best method that has been devised for preventing field distortion and securing good commutation under all loads is the use of interpoles.

These are small, auxiliary poles placed mid-way between the main poles and provided with a winding in series with the armature. Fig. 16 shows the frame of a two-pole, interpole machine, one main and one auxiliary pole being shown with winding in place and the others without. The effect of the interpole flux is to oppose that due to the cross ampere-turns of the armature, thus offsetting the shifting of the direction of main flux and maintaining the neutral field zone in a fixed position.

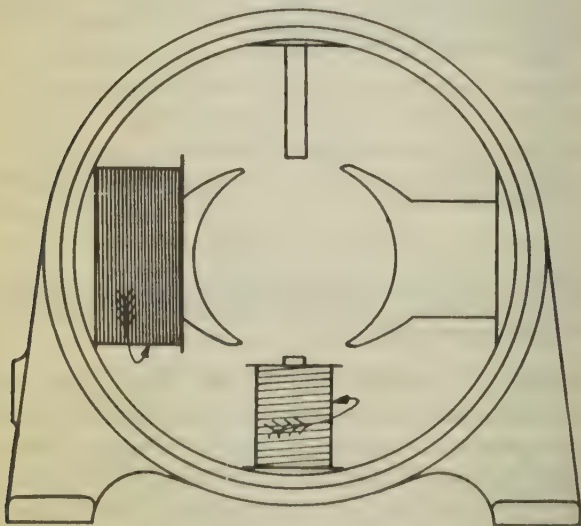


FIG. 16.—Showing typical field frame for two-pole machine with interpoles. Direction of field currents shown for clockwise rotation of generator armature. Interpole *precedes* main field pole of like polarity on generator. Interpole *follows* main field pole of like polarity on motor.

By making the interpole winding somewhat stronger than is necessary to counteract the armature cross turns it not only corrects field distortion in the commutating zone, but induces a voltage in the coils undergoing commutation which neutralizes reactance voltage in these coils and accomplishes the reversal of the current in the coils before the short circuit is broken. Machines with properly designed interpoles can be operated sparklessly over their entire load range without shifting of the brushes, provided the core of the interpole is not saturated under heavy loads.

The effect of the interpole winding can be more readily understood by reference to the accompanying rectified curves of magnetic distribution.

Fig. 17 illustrates the flux distribution of a non-interpole generator. Curves are shown for no-load and full-load. These show the crowding of the flux away from the leading to the trailing pole tip when the machine is loaded. They also show the shifting of the neutral or point of zero flux.

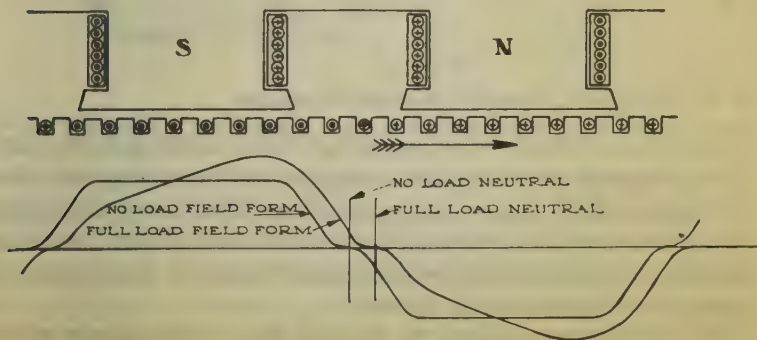


FIG. 17.—Showing form of magnetic field on non-interpole generator.

Fig. 18 shows similar curves for a machine with interpoles. It will be seen that the flux distortion immediately under the main pole faces still takes place as the load comes on, but the shifting of the commutating zone is eliminated by the interpole flux and the commutating point held stationary for all loads. The dip in the full-load flux distribution curve at the commutation point represents the extra flux necessary to neutralize the reactance of the commutated coil and reverse the current in it during the period of commutation.

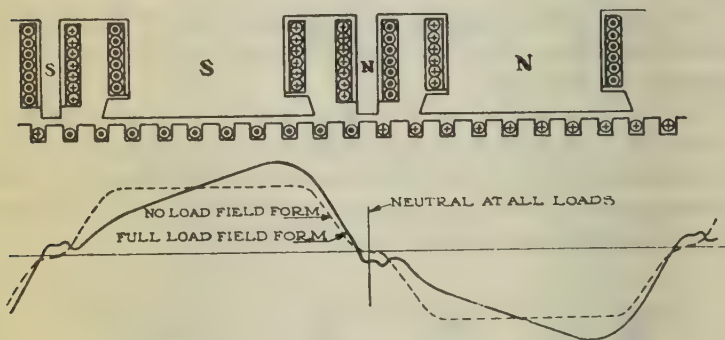


FIG. 18.—Showing form of magnetic field on interpole generator.

The magnetomotive (magnetizing) forces existing in the parts of an interpole generator are composed of three elements; that in the main field, that in the interpole and that in the armature. It is the latter that causes the distortion of the flux under the main poles and is largely beyond the influence of the interpoles, except in the commutating zone.

By distributing in slots on the pole faces a winding in series with the armature and of corresponding number of turns, but with current in opposite direction to that in adjacent armature

conductors, it is possible to create a *m.m.f.* opposed to the armature *m.m.f.* and with the aid of the interpoles, almost perfectly compensate the effects of the armature winding. Fig. 19 shows the flux distribution in a compensated generator.

The value of the compensating pole face winding lies in the reduction of the peak voltage which is generated in the armature coils when they pass through the distorted flux seen in figs. 17 and 18. This high voltage per coil puts an added strain on the insulation, tends to produce ring-figure and may even lead to the machine flashing over.

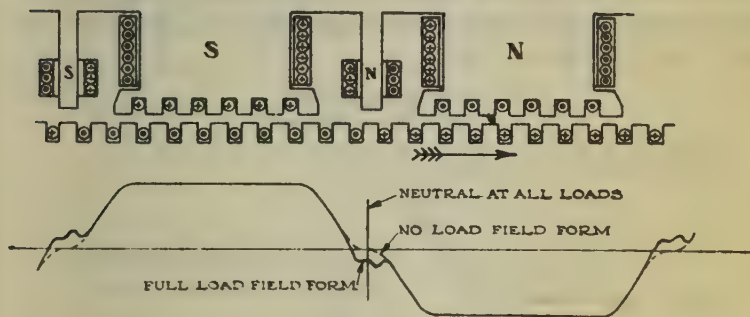


FIG. 19.—Illustrating form of magnetic field on interpole generator with compensating pole face winding.

With distortion of the field flux under the pole faces eliminated by means of the compensating winding, the danger of such troubles is minimized, and a higher average voltage per armature coil becomes permissible. In the case of crowded designs, such as high capacity, 60 cycle rotary converters, where physical limitations must be approached as closely as possible, the compensating winding has made possible designs which otherwise could not have been attempted.

The Commutation Period.—In the study of commutation it should be borne in mind that perfect neutralization of voltages is seldom, if ever, attained in practice, although it might be implied from the foregoing discussion that such is the case. A given fixed voltage could be easily compensated, but the voltages in the commutating coil are undergoing change of value throughout the period of commutation. Perfect compensation would require that the time rate of change, as well as the average and maximum values, must be matched by the neutralizing voltage. If accomplished, we should then have “straight line” commutation, that is, the time current curve for the short-circuited coil would be a straight line, as shown in fig. 20, and the current density over the full thickness of the brush face would be uniform.

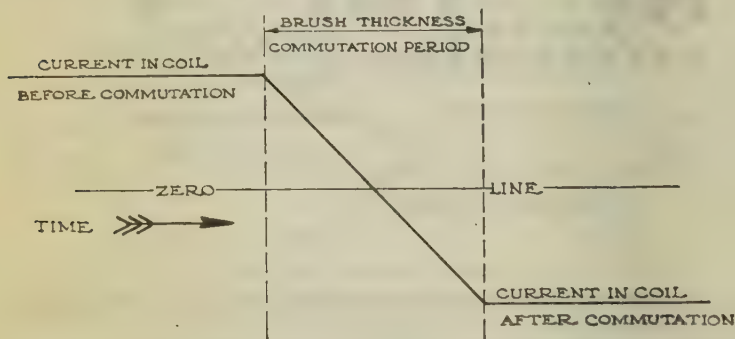


FIG. 20.—Showing *straight line* commutation characteristic.

While straight line or linear commutation is very difficult to attain, it is practicable to obtain a commutation curve approximating the sinusoidal curve shown in fig. 21. Commutation on such a basis is very satisfactory, since the short-circuit current is reversed and re-established at load value before the short-circuit is broken.

It will also be seen from fig. 22 which shows the average local current density across the brush face, that extreme densities are not encountered with sinusoidal commutation. If the compensating voltages are too weak, the condition known as under-commutation will be encountered. The current in a coil just short-circuited will increase for an instant before reversal begins, and will not be established at the reversed load value when the short circuit is broken. As a result, an arc or spark is drawn between the brush and the receding commutator segment while the current adjustment in the coil is being completed.

Over-commutation, by establishing too large a reversed current in the commutated coil likewise produces sparking when one of the connected commutator bars moves from under the brush.

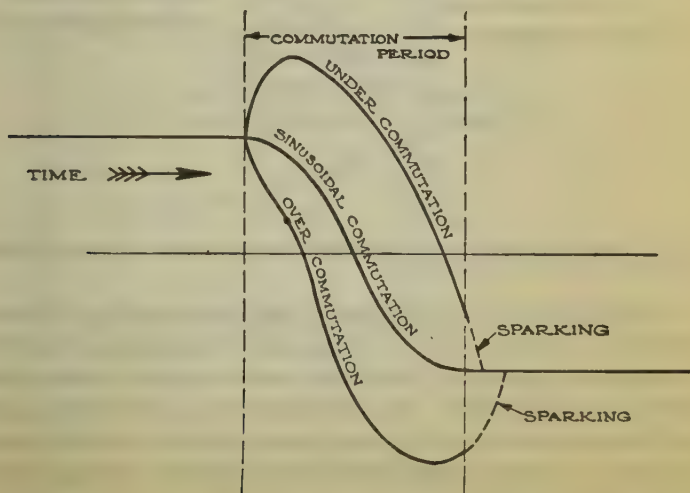


FIG. 21.—Types of commutation curves usually encountered in practice.

Typical short-circuit current curves for under and over commutation are shown in fig. 21. In fig. 22 it may be seen that with under commutation, the current is reversed at the leading edge of the brush face and reaches a very high density at the trailing edge. In the case of over commutation, high density is encountered at the leading edge of the brush and a reversal of current at the trailing edge.

It may be seen from a comparison of curves in figs. 21 and 22 that a badly distorted curve of short circuit current might be, as it frequently is, the cause of extreme current densities at certain points on the brush face.

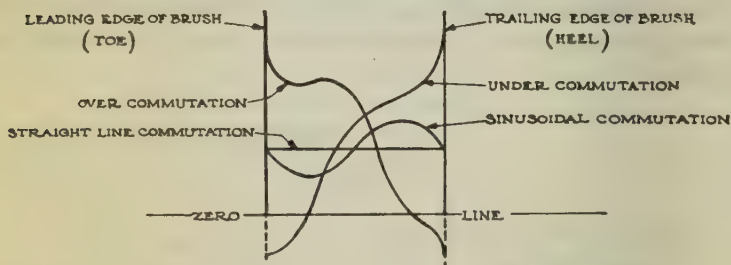
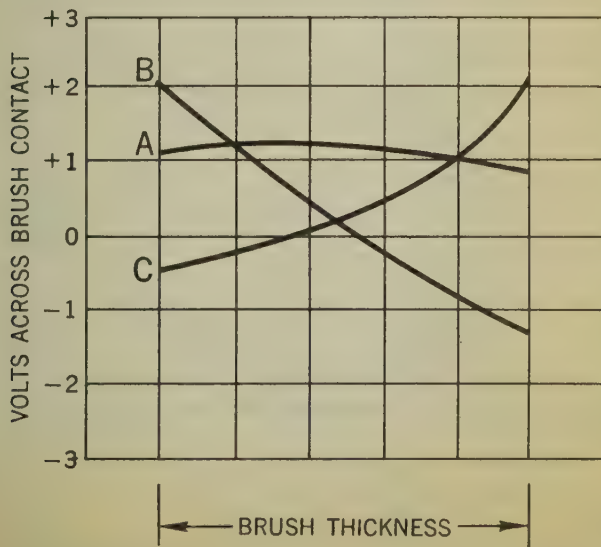
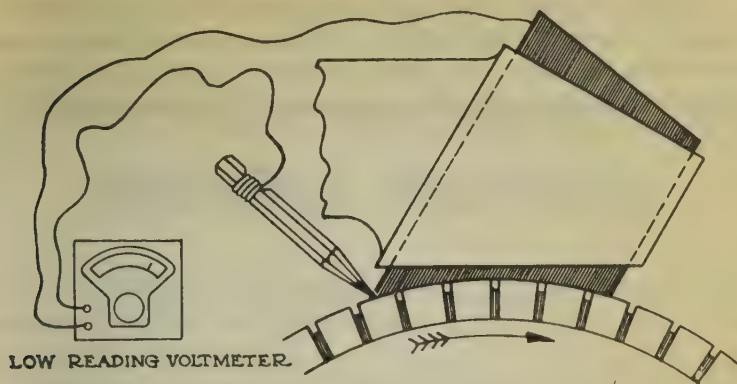


FIG. 22.—Showing curves of average local current density at brush face under commutation conditions shown in figs. 20 and 21.

A good idea of the character of the commutation curve on a particular machine may be obtained by measuring the voltage drop between brush and revolving commutator at several points across the brush face. Fig. 23 illustrates a method for making such measurements and typical curves obtained in this manner. The lead of a hard pencil makes an excellent terminal for this purpose. Linear commutation will, of course, show the same voltage drop across the entire face.



FIGS. 23 and 24.—Showing method of measuring voltage drop between brush and revolving commutator and voltage characteristics.

Curve *A*, fig. 24, indicates a close approach to linear commutation. Curve *B*, indicating by excessive drop a high current density at the toe of the brush and also indicating reversal of current at the heel, shows a condition of over-commutation.

CHAPTER 19

Direct Current Armature Winding Methods

The Gramme Ring Winding.—Although the Gramme ring armature is now very seldom used, its principle is given here because of its simplicity.

Here a rotating soft iron ring is mounted between the poles of an electromagnet as shown in fig. 1. The ring serves to

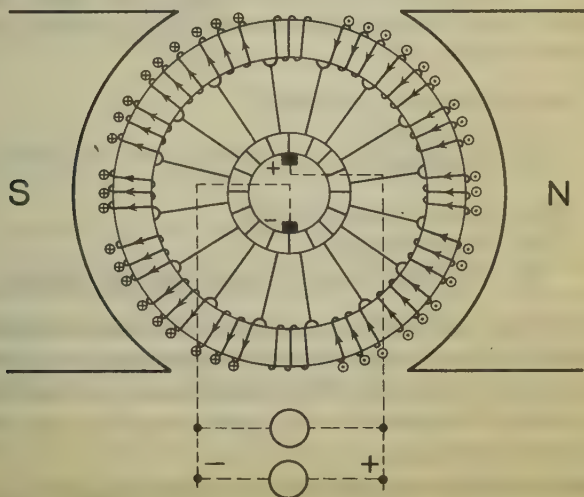


FIG. 1.—Illustrating a typical Gramme ring winding.

carry the magnetic flux across from one pole into another. A continuous coil of copper wire is wound on the ring as shown in fig. 1, threading through the hole as indicated.

Taps are taken from the wire at every turn and connected to the commutation bars, which are connected to the outside circuit by means of a pair of brushes. Since the conductors which lie inside the ring cut no flux, being merely connectors for the active conductors which lie on the surface of the wire, and also because that form wound coils cannot be employed, this type of winding is expensive and now practically obsolete.

Types of Armature Winding.—By employing what is known as the *drum winding*, the shortcomings of the previously mentioned Gramme ring winding are eliminated. The drum winding is used in practically all direct current machines, and may be classified according to the methods of connecting the coils to the commutator as:

1. **Lap** (multiple or parallel).
 - (a) Simplex lap.
 - (b) Multiplex lap.
2. **Wave** (series or two-circuit).
 - (a) Simplex wave.
 - (b) Multiplex wave or series parallel winding.

Lap windings generally known as *parallel windings* are commonly used for lower voltages and machines which are required to carry heavy currents. The term *lap* is derived from the lapping back of the coils as they are wound on the armature core as shown in fig. 2.

A simplex lap winding has only two paths through the armature from each brush, and always requires as many brushes as there are poles in the machine.

A duplex lap winding has four paths through the armature from each brush.

The lap winding is placed on the surface of the armature in the slots. There are two sides in each coil, *a* and *b*, which are active in generating an *e.m.f.* The sides of each coil should be separated by about one pole pitch, that is, the distance between the centers of adjacent poles.

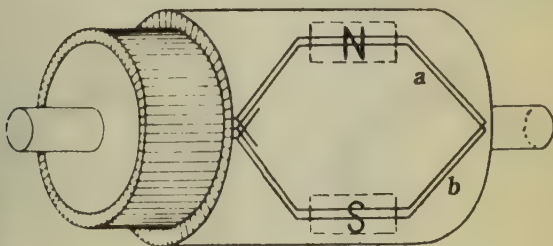


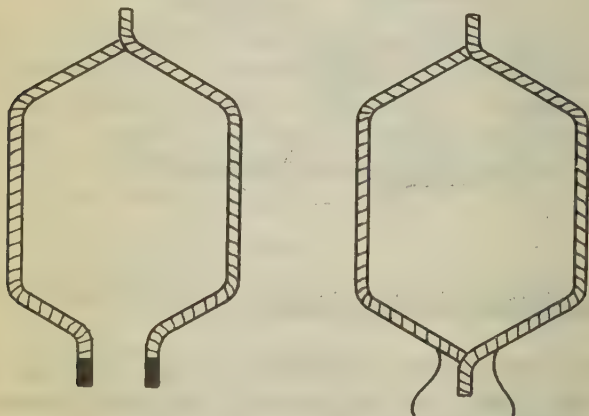
FIG. 2.—Lap winding illustrating the relative position of one winding element or coil side of two turns on the armature of a four pole machine.

Thus, if one coil side is under an *N* pole, the other side is under an *S* pole. As both move in the same direction but under different polarities, the *e.m.f.*'s of these conductors, in space, will be in opposite directions. It will readily be observed that owing to the manner in which these conductors are connected to the commutator, the *e.m.f.*'s in the two coil sides are additive.

A coil may consist of one or several turns as shown in figs. 3 and 4. However, it is customary for the sake of simplicity to show the coils as if consisting only of one turn in winding diagrams.

The coils are usually wound with the necessary number of turns by a machine, and are then wrapped with cotton, varnished cambric or mica tape. It is then bent in the proper shape by another machine.

It is customary to place two coil sides in each slot, one coil side lying at the top and the other side of the same coil at the bottom of another slot. This method makes it possible to place the coils adjacent to each other in a systematic manner, passing from the bottom to the top layer by means of a peculiar twist in the ends of the coil.

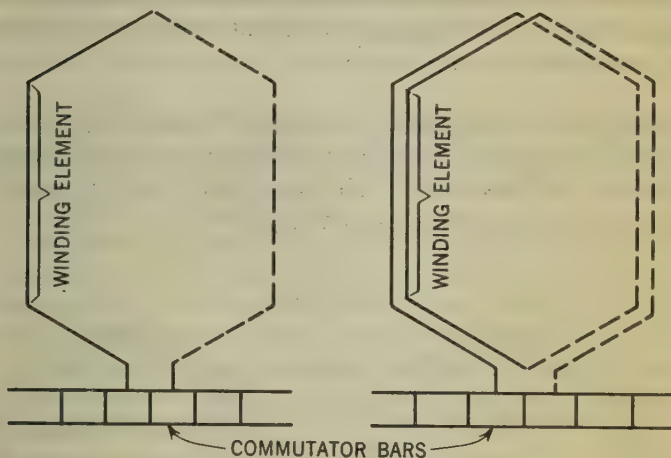


FIGS. 3 and 4.—Type of coils used in a lap winding.

For the sake of clearness the following terms most commonly applied to the armature windings will be defined:

Armature Coil.—All the conductors on the armature connected in series between two consecutive connections to the commutator. It may consist of one or more turns.

Coil Element.—The group of wires, figs. 5 and 6, constituting the side of a coil and usually wrapped together with tape as a unit, is termed a *winding element*. Since each coil has two sides, there will always be twice as many coil elements as there are coils in a winding.



FIGS. 5 and 6.—Showing single coil representing a two-turn coil of an armature winding.

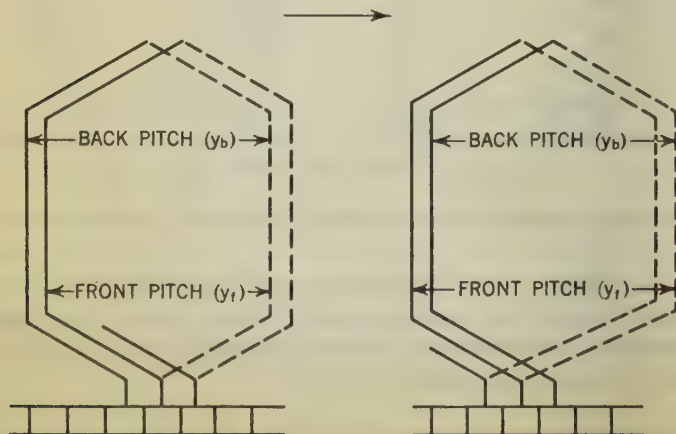
Coil Pitch.—The number of slots spanned by one coil is termed the *coil* or *winding pitch*. When a coil spans exactly the distance between the center of the adjacent field poles, it is said to have a *full pitch* coil.

Fractional Pitch Coils.—In case the coil spans less than full pitch, it is said to have a *fractional pitch* and such a winding is often termed a *short cord winding*.

These are frequently used because they have shorter end connections, thus requiring less copper and are easier to install in the slots. In addition armature reaction is reduced since the currents in the neutral zone flow partly in opposite directions and neutralize each other.

Front Pitch.—The distance between two sides of a coil connected to the same commutator segment, measured in coil sides at the front or commutator end of the armature is termed the *front pitch*.

Back Pitch.—Similarly the distance between the two sides of a coil measured in coil sides, at the back end of the armature, is termed the *back pitch*. The front pitch may be greater or less than the back pitch, but not equal to it.



FIGS. 7 and 8.—Illustrating a progressive and retrogressive lap winding, respectively.

Commutator Pitch.—Distance between the two commutator bars connected to the ends of a coil, measured in commutator bars.

Meaning of Terms *Progressive* and *Retrogressive*.—If the front pitch is less than the back pitch, the winding is termed *progressive*, that is, it advances in a clockwise direction when viewed from the commutator end. On the other hand, if the front pitch is greater than the back pitch, the winding is termed *retrogressive*, advancing in a counterclockwise direction.

Type of Winding Diagrams.—In the construction of armatures, instructions are usually given in forms of diagrams and tables. There are usually two types of winding diagrams, termed *radial* and *developed* view.

In the radial diagram the conductors of the armature are represented by short radial lines, while the end connectors are represented by curves or zig zags, those at one end of the armature being drawn within, those at the other end without the circumference of the armature. With the radial diagram it is easier to follow the circuits and to distinguish the back and front pitch of the winding.

The developed diagram is a mode of representation, in which the armature winding is considered as though the entire structure had been laid out on a flat surface.

Tracing a Simplex Lap Winding.—A typical diagram of a lap winding is shown in fig. 9. A tracing of the circuit shows that starting at the brush *B* and passing successively through the conductors 7, 12, 9 and 14, the brush *C* is reached, and that the *e.m.f.*'s induced in each conductor is that in the direction of travel of the point which traces out this path. Again starting at brush *B* and passing successively through the conductors

10, 5, 8 and 3, the brush *A* is reached, the induced *e.m.f.*'s in these conductors likewise being in the direction of travel of the point which traces out this path.

It follows that the brush *B* is negative and that both brushes *A* and *C* are positive and at the same potential above brush *B*. Brushes *A* and *C* may, therefore, be connected together in parallel as indicated. Following through the two paths through the winding from brush *C* to brushes *B* and *D*, respectively, it will be observed that the brush *D* is at the same potential as brush *B*. Now since both brushes *B* and *D* are at the same negative potential, they may also be connected together in parallel as indicated.

This winding requires as many brushes as there are poles in the machine.

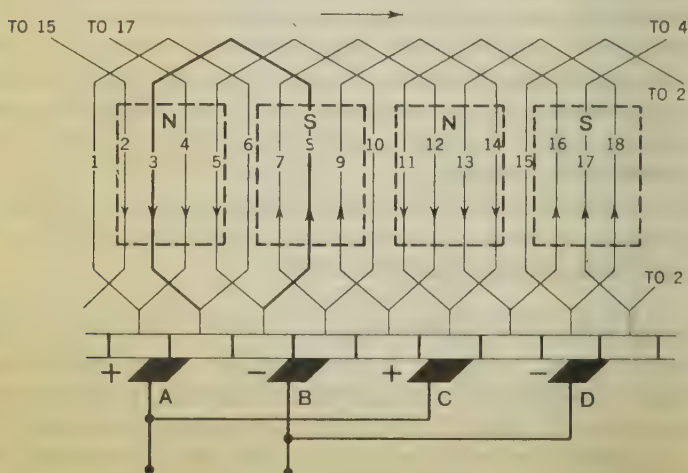


FIG. 9.—Simplex four pole lap winding.

Winding Tables.—As previously pointed out, armature winding instructions are usually computed in table forms, which are conveniently used not only for completion of the winding, but also for checking the finished winding. By inspection it may be determined whether or not each conductor is included once, and only once, and also whether the winding closes at the same conductor at which it began. With reference to fig. 9, starting at 1, the table will progress as follows:

1-6-3-8-5-10-7-12-9-14-11-16-13-18-15-2-17-4-1.

Other winding diagrams may be put in table form in a similar manner.

Symbols Used in Lap Windings.—The difference in construction between a wave and lap winding pertains to the method of connecting together the individual coils, they being easily distinguished by an inspection of the end connections. Thus in the *wave winding* the end connections at the front and rear of the armature continue in the same direction around the armature as shown in fig. 11, while in the lap winding the front and rear connections lead in opposite directions as indicated in fig. 10.

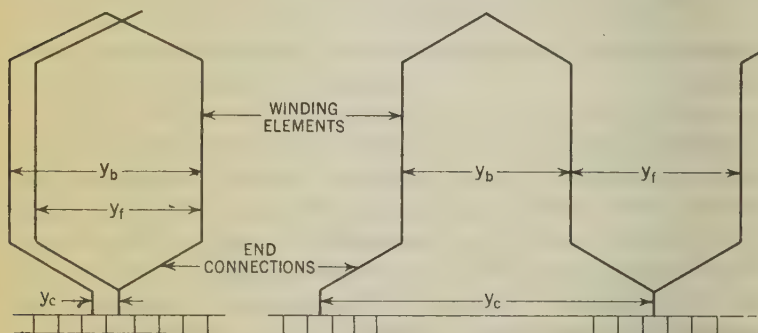
In determining the number of coils to be used in an armature winding there are certain rules that must be observed, which are briefly as follows:

1. The front and back pitch must both be odd numbers, and in the lap winding must differ by *two* or some multiple thereof.
2. In the wave winding the front and back pitch may be equal or may differ by *two* or some multiple thereof.
3. In the lap winding the front and back pitches are of opposite sign, that is, they are laid off in opposite

directions on the armature, while in the wave winding they are of the same sign.

4. The commutator pitch is equal to the average of the front and back pitches.

In applying these rules and the formulae which follow, it is necessary when slotted armatures are used to adhere to a definite method of numbering the elements of the windings.



FIGS. 10 and 11.—Illustrating a lap and wave winding, respectively, and symbols used in winding formulae.

If the winding element, figs. 10 and 11, lying in the top slots of fig. 12 are given odd numbers, it will readily be observed that since one side of a coil lies in the bottom of the slot, the other side of the same coil must lie in the top of some other slot. Thus with reference to figs. 10 and 11, y_b and y_f must both have odd numbers if the winding is to be placed properly on the armature.

It follows that the front and back pitches must differ from each other by 2. Thus for the lap winding in fig. 10 we obtain:

$$\text{back pitch} = y_b = \frac{s \pm b}{2p} \quad (1)$$

$$\text{front pitch} = y_f = y_b = \pm 2 \quad (2)$$

$$\text{average pitch} = y \pm 1 \quad (3)$$

$$\text{commutator pitch} = y_c \pm 1 \quad (4)$$

Where s = number of half coils or elements in the winding.

p = number of pairs of poles in the machine.

b = a number which will make y_b and y_f odd integers (whole numbers).

For $b = 0$, the back pitch becomes equal to the whole pitch; if b is positive, y_b becomes greater than the pole pitch and the winding is termed progressive; if b is negative y_b becomes less than the pole pitch and the winding is termed retrogressive. As a rule b is negative and y_b becomes less than the pole pitch, that is, y_b is made equal or less than the pole pitch.

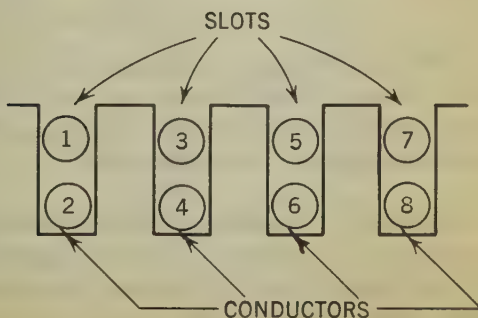


FIG. 12.—Showing method of designating numbers to coil elements.

The simplex lap winding has as many parallel circuits as there are poles in the machine. However, in cases where it is necessary to obtain a heavy current, duplex or triplex lap windings are sometimes used. The duplex lap winding is obtained by placing two similar windings on the same armature and connecting the even numbered commutator bars to one winding and the odd numbered ones to the second winding. Similarly, in the triplex lap winding, each section of the winding would connect to one-third of the commutator bars. For these windings:

$$y_b = \frac{s \pm b}{2p}, \text{ and} \quad (5)$$

$$y_f = \frac{s \pm b}{2p} \pm 2m; \quad (6)$$

$$y_c = \frac{y_b - y_f}{2} = \pm m \quad (7)$$

$$y = y_b - y_f = \pm 2m \quad (8)$$

Where m = an integer greater than one, that is, two for a double winding, three for a triple winding, etc., if the number of commutator bars is exactly divisible by m the several windings will be entirely separate from each other.

Multiplex Windings.—Multiplex windings are being used where the armature is required to carry a current which is higher than that allowed for the simplex lap type. Double layer windings of this type are shown in figs. 13 and 14.

The winding shown in fig. 13 has 16 coils in 16 slots. An inspection shows that $s = 32$, $b = 4$, and $p = 2$ (4 poles). With reference to equations (1) and (2) we obtain:

$$y_b = \frac{32 - 4}{4} = 7 \text{ and } y_f = \frac{32 - 4}{4} + 2 = 9.$$

In this winding the coil pitch y_b is equal to the pole pitch; therefore, it is a full pitch winding.

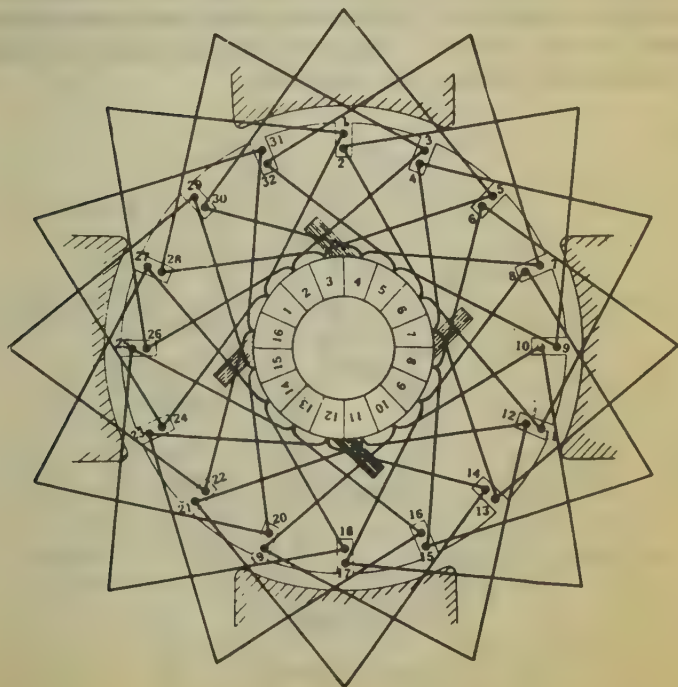


FIG. 13.—Four pole, 16 slot, multiplex lap winding.

The winding shown in fig. 14 has 26 slots and 4 poles with only alternate slots filled.

The back pitch y_b is 13, and coil element 1 connects to element 14 and then connects to 5 on the front of the armature, making the front pitch $y_f = 9$.

Instead of returning to the element differing by 2 from the initial element, the return is made to a coil side differing by 4. It should be noted that the alternate slots and commutator segments are left vacant. Also this winding closes on itself after passing once around the armature.

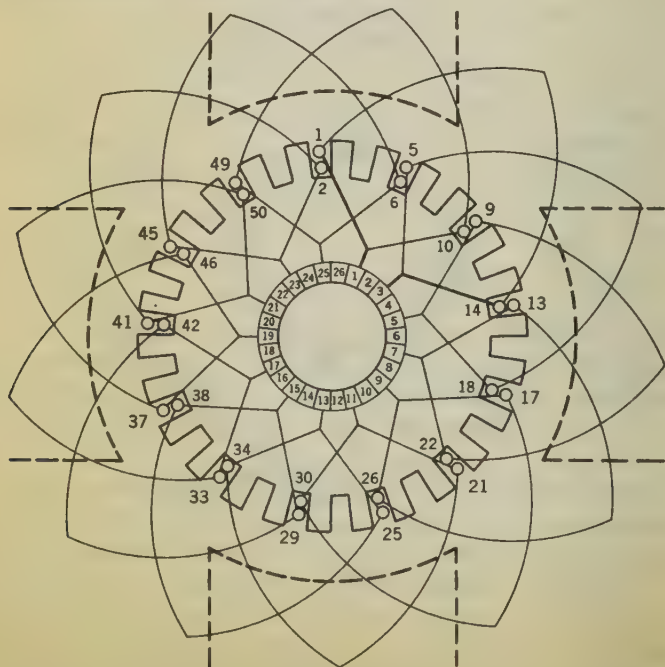


FIG. 14.—Illustrating a four pole, 26 slot, multiplex lap winding (only one winding shown).

In an armature wound in this manner a duplicate winding could be placed in the vacant slots. This additional winding would also close itself. These two windings would then be separate from each other on the armature, but connected in the same manner as the winding shown and to its proper commutator segment.

A multiplex lap winding in which the coil pitch is considerably less than the pole pitch is shown in fig. 15. In this case $s = 64$, $b = 12$ and $p = 2$. The number of slots = 16. Then:

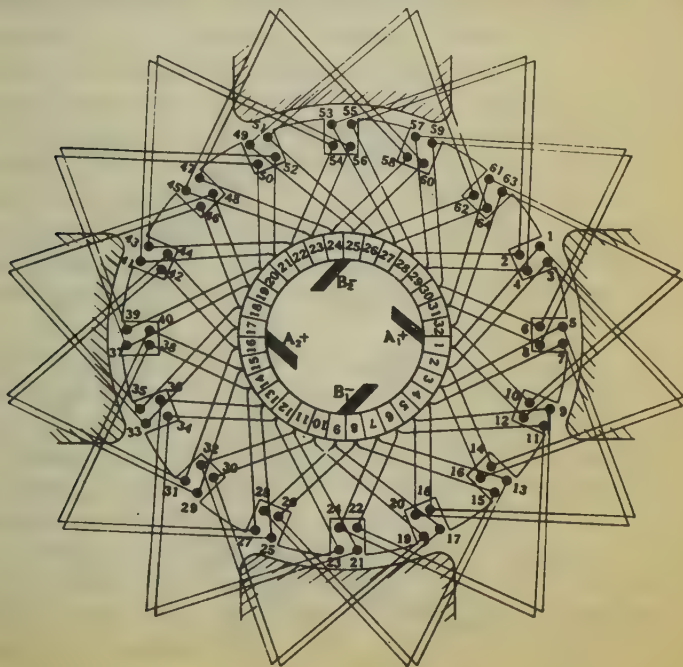


FIG. 15.—Four pole, 16 slot, multiplex lap winding.

$$y_b = \frac{64 - 12}{4} = 13$$

and

$$y_f = 13 - 2 = 11.$$

This type of winding is generally known as a chord or chorded winding in distinction from the full pitch winding.

A duplex lap winding composed of 36 coils placed in 18 slots and 18 coils for each winding, is shown in fig. 16. Here, $s = 72$, with the number of commutator bars = 36; $p = 2$, $m = 2$. Since in this case $s/2p$ is an even number = 18, b is taken as 4.

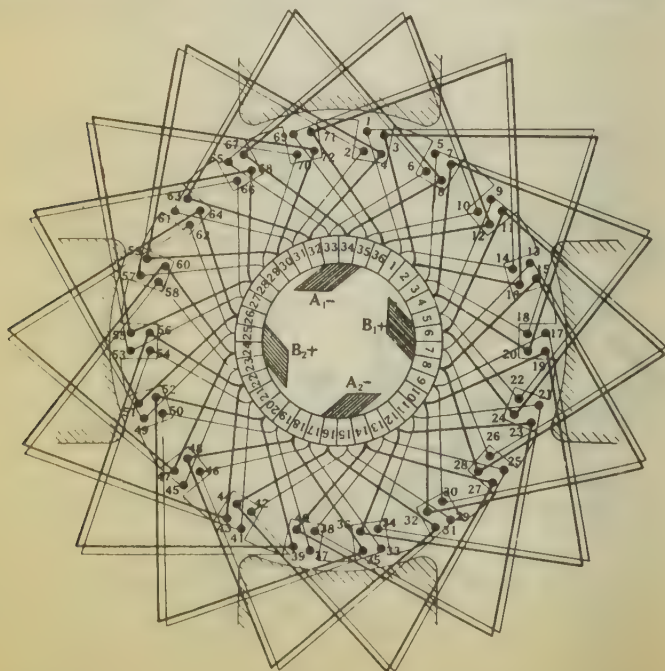


FIG. 16.—Four pole, 18 slot, multiplex lap winding.

Therefore:

$$y_b = \frac{72 - 4}{4} = 17$$

$$y_f = 17 - 4 = 13$$

$$\text{and commutator pitch } y_c = \frac{17 - 13}{2} = 2.$$

Since the number of commutator bars = 36 and the commutator pitch $y_c = 2$, have the common divisor 2, two distinct windings are obtained. Beginning with bar 1 and tracing through the winding, it may be seen that the winding completes itself after going around the armature once and connecting to one-half of the commutator bars; this winding has $2p = 4$ parallel circuits. Similarly the second winding embraces one-half of the coils and commutator bars, its coil fitting in between those of the first winding, and has also four parallel circuits. Therefore, the two windings together give eight parallel circuits.

Another duplex lap winding is illustrated in fig. 17. Here one of the two distinct windings is shown dotted for the sake of clarity. It should be noted that this winding does not close after passing once around the armature, but must pass around the armature once more before closing as indicated. The winding does not return to commutator segment number 1, but terminates at commutator segment number 2. The second winding shown with dotted lines starts at segment number 2 and closes at segment number 1 after passing once around the armature.

Single and Double Re-Entrant Windings.—The difference between a single and double re-entrant winding may best be illustrated with reference to figs. 18 and 19. When each of the two windings passes twice around the armature but closes only once, it is termed single re-entrant. When each of the two windings closes upon itself, the winding is termed double-re-entrant. With this latter type of winding it is necessary that the brush span at least two commutator segments.

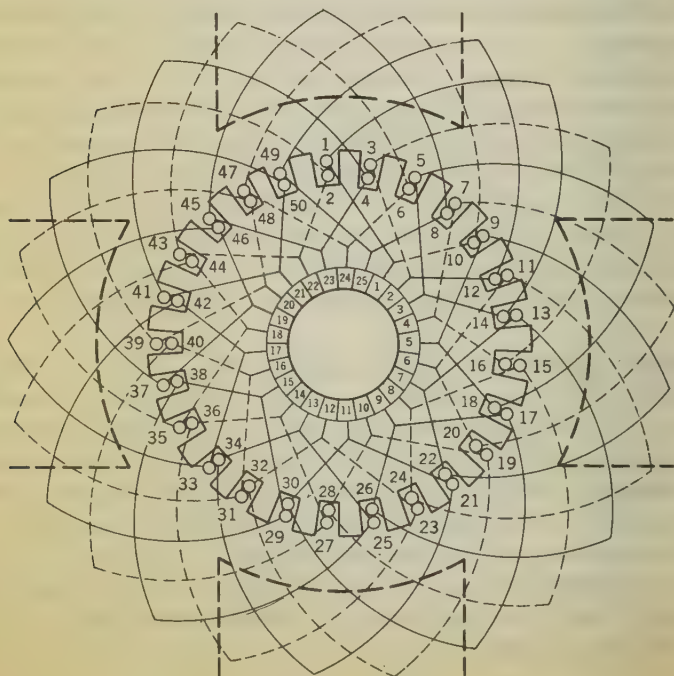
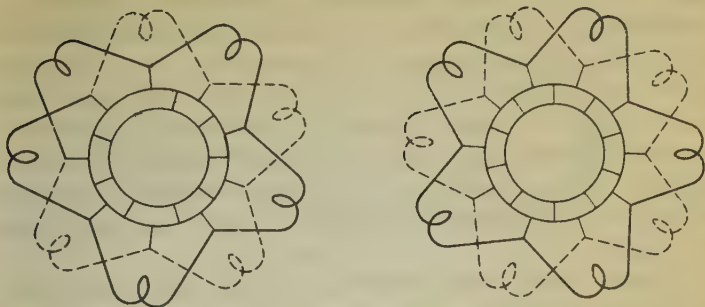


FIG. 17.—Four pole, 25 slot, multiplex lap winding.



FIGS. 18 and 19.—Schematic illustration of a duplex single and double re-entrant winding, respectively.

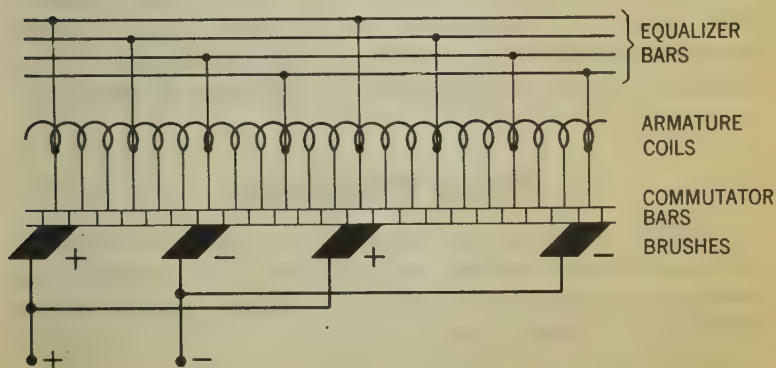


FIG. 20.—Schematic diagram of equalizer circuit showing four of six brushes.

Equalizer Connections in Lap Windings.—These are provided in parallel wound armatures to eliminate the effects of “unbalancing” by which the current divides unequally among the several paths through the armature. To relieve the brushes of this extra current, several points in the armature which should be simultaneously at the same potential are connected together as in fig. 20 by heavy copper bars termed equalizers, thus allowing the circulating currents to flow from one point in the armature to another without passing through the brushes.

If there were perfect symmetry in the field system of a machine, no current would flow along such connectors. Owing to imperfect symmetry, the induction in the various sections of the winding may be unequal and the current not equally distributed.

To exactly equalize the current, every commutator segment should have an equalizer connection. This would require a large number of connectors, but in practice only enough equalizer connections are made to keep variations in brush current within the limit required by the danger of sparking.

Wave Windings

General.—Whereas *lap windings* are generally used in machines required to carry a high current at low voltage, *wave windings* are used mainly where the current is low and the voltage is of a higher value.

The term *wave winding* (also called series or two-circuit winding) is derived from the wave path the winding takes through the slots of the armature, as illustrated in figs. 21 and 22.

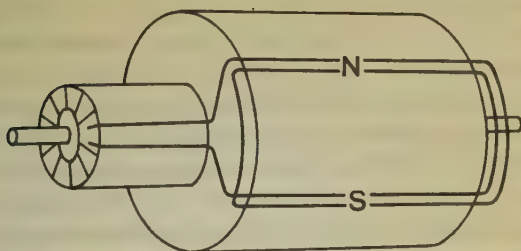


FIG. 21.—Wave winding showing the relative position of one winding element (or coil side) of two turns on the armature of a four pole machine.

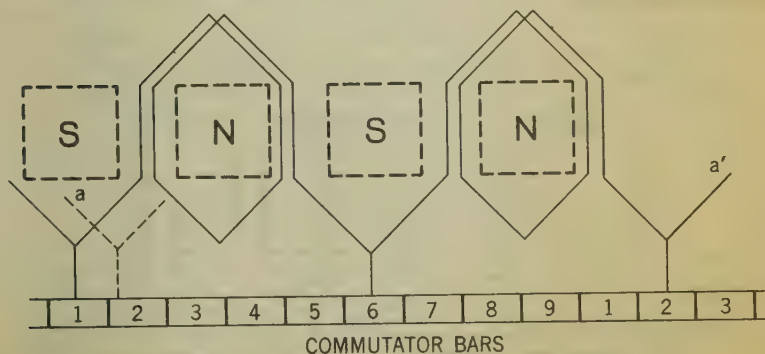


FIG. 22.—Illustrating wave winding diagrams of a four pole armature such as that given in fig. 21. It will be observed that the finish end of one coil is joined to the commutator bar and connected to the start of the next coil under the adjacent pair of poles. In the illustration *a* is a continuation of *a'*.

Tracing a Simplex Wave Winding.—A typical diagram of a simplex wave winding is shown in fig. 23. A tracing of the circuit shows that starting at brush *B*, and passing successively through conductors 11, 16, 3, 8, 13 and 18, brush *A* is reached and that the *e.m.f.*'s in each of these conductors is in the opposite direction of travel of the point which traces out this path. Again starting at brush *B*, and passing successively through conductors 6, 1, 14, 9, 4, 17, 12 and 7, the brush *A* is reached. This series of conductors are forming the second path between the brushes.

It follows that brush *B* is positive and brush *A* is negative, as marked in our diagram.

It should be noted that in an actual machine there are several times as many conductors as shown in our simplified diagram. The principles, however, remain the same. This winding requires only two brushes irrespective of the number of poles in the machine.

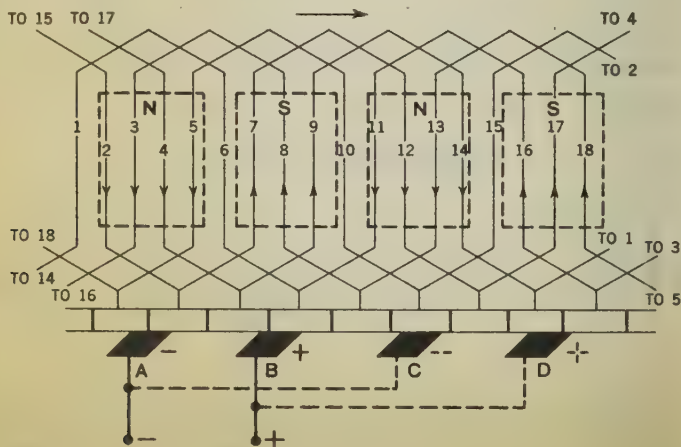
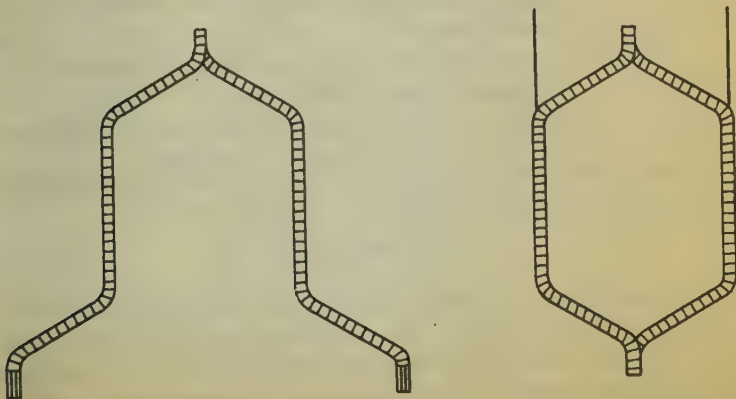


FIG. 23.—Showing a simplex, four pole, wave winding.

If it is desired, as many brushes as there are poles may be used; thus, with reference to fig. 23, a second positive brush *D* may be employed, connected to brush *B*, and also a second negative brush *C* connected to brush *A*. It may be observed that between brushes *B* and *D* there are only two armature conductors, 6 and 1, in which there is practically no induced *e.m.f.*'s; hence the external connections between *B* and *D* does not short circuit any of the active conductors. Similarly, between brushes *A* and *C* there are the conductors 5 and 10, or 2 and 15, in which there is practically no induced *e.m.f.*'s or at least would not be in an actual machine having a large number of conductors.

Wave wound coils, figs. 24 and 25, as lap wound coils may have more than one turn, but since the number of turns does not affect the form of the winding, all wave windings are shown as having only one turn.



FIGS. 24 and 25.—Illustrating type of coils used in wave windings.

Symbols Used in Wave Windings.—In wave windings, as in lap windings, the number of elements spanned on the pulley end is termed the back pitch y_b and the number of elements spanned at the commutator end is termed the front pitch y_f .

This is illustrated in fig. 11. It should be observed here that the pitch is always forward in contrast to the lap winding where it is alternately forward and backward.

With reference to fig. 11, the following formulae are obtained:

$$\text{Winding pitch} = y = y_b + y_f = \frac{s \pm 2}{p} = 2 y_c \quad (9)$$

$$\text{Commutator pitch} = y_c = \frac{y_b + y_f}{2} = \frac{k \pm 1}{p} \quad (10)$$

Where y = winding pitch.

y_b = back pitch.

y_f = front pitch.

s = the number of half coils or elements in the winding.

p = number of pairs of poles in the machine.

y_c = commutator pitch.

k = number of commutator bars in the machine.

It follows from the foregoing that the number of commutator bars must satisfy the equation:

$$k = p \times y_c \pm 1 \quad (11)$$

As before y_b and y_f must be odd integers and y must be a whole number. In this case the back pitch is very nearly equal to the pole pitch and the sum of the front and back pitches is very nearly equal to double the pole pitch. If y_b is decreased as in the case of a chord winding, then y_f must be increased so that the sum $y_b + y_f$ remains constant.

A four-pole wave winding having 13 coils is shown in fig. 26. Here $y_c = 6$ and $p = 2$. Then with reference to equation (12) $k = 2 \times 6 \pm 1 = 11$ or 13 (in this case, 13) and $y_b + y_f = 2y_c = 12$, for $k = 13$, $s = 26$, $y_b = 7$ and $y_f = 5$.

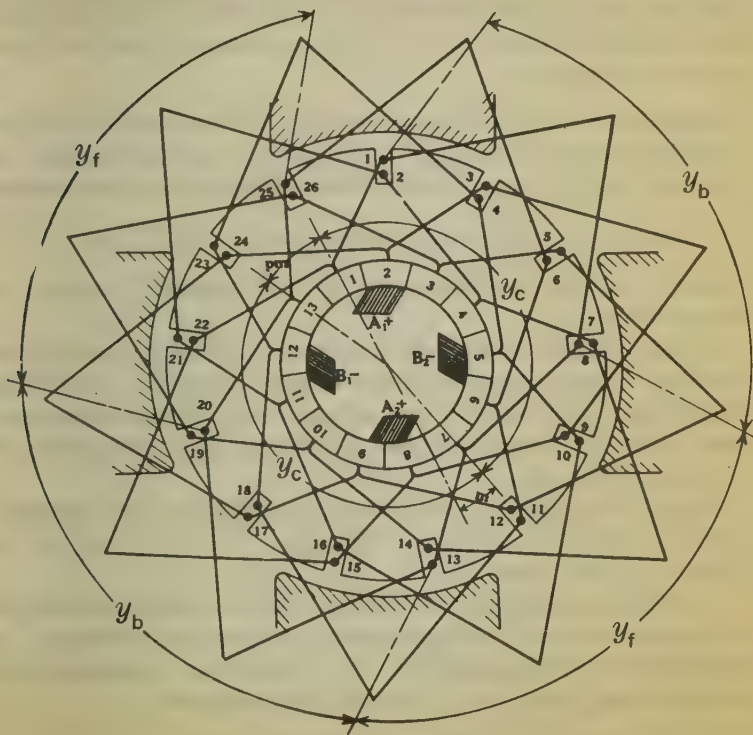


FIG. 26.—Illustrating a four pole wave winding.

Beginning with bar number 1, it connects with $(1 + y_b = 1 + 7 = 8)$, elements 1 and 8 forming the two sides of a coil. As the commutator pitch is $(y_c = 6)$ and the front pitch 5, from element number 8 the circuit passes across the front end of the armature to elements $(8 + 5 = 13)$ and in so doing connects to commutator bar $(7 + y_c = 13)$, the circuit is found to have traveled around the commutator a distance of $2y_c$ bars and have reached the bar $(1 + py_c)$, at a distance of one bar from the starting point.

Denoting by m , the amount which y_c differs from the double pole pitch (in this case, half a bar), $pm = 1$ is the amount by which py_c or $(2y_c)$ deviates from the starting point, bar number

1. Then $py_c = k \pm pm$, or since, $m = a/p$; $y_c = \frac{k \pm a}{p}$,

where a is the number of pairs of parallel circuits in the armature.

In this type of winding the number of parallel circuits in the armature is *two* regardless of the number of poles. A winding of this type is particularly well adapted for small and moderate-sized machines where it is desirable to keep the number of coils as small as possible.

Fig. 27 illustrates a 17-slot four-pole simplex wave winding. Here $y_b = 9$ and $p = 2$, $y_f = 7$, then $y_c = 8$. $k = 2 \times 8 \pm 1 = 17$ or 15 (in this case, 17).

A wave winding may be *duplex*, *triplex*, or have any degree of multiplicity in the same manner as the lap winding. A simplex wave winding always has two paths, a duplex wave winding four paths, etc., through the armature.

Fig. 28 illustrates a 26-slot four-pole winding in which only every alternate slot is filled, there are two coil sides per slot.

Here $y_b = 13$ and coil side 1 connects to the coil side 14 on the back of the armature. Coil side 14 then connects to 25 on the front of the armature, making the front pitch $y_f = 11$. Therefore, the commutator pitch $y_c = 12$. It should be observed that if the number of slots were 24 instead of 26 the winding would not have filled the alternate slots and closed, but would

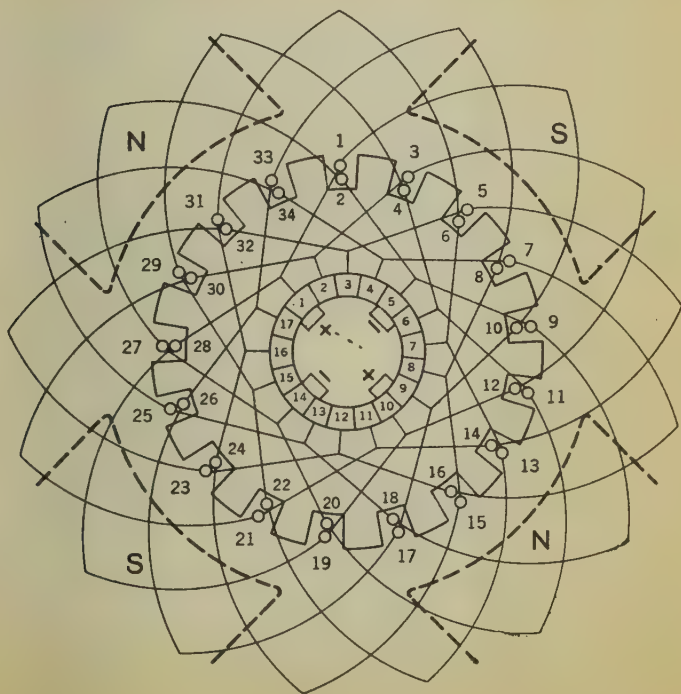


FIG. 27.—Four pole wave winding.

have returned to a slot and commutator segment to the right or left of the one from which it started. In this case the winding will close only after the remaining alternate slots are filled.

A winding of this latter type is illustrated in fig. 29, and is classified as a *duplex single re-entrant retrogressive wave winding*.



FIG. 28.—Four pole, 26 slot, wave winding.

It follows from this, that the multiplicity and re-entrancy for lap windings also applies for wave windings, that is, in a wave winding, multiplicity relates to the number of independent windings on the armature, whereas re-entrancy relates to the fraction of the armature that must be traced before returning to the commutator segment from which the winding began.

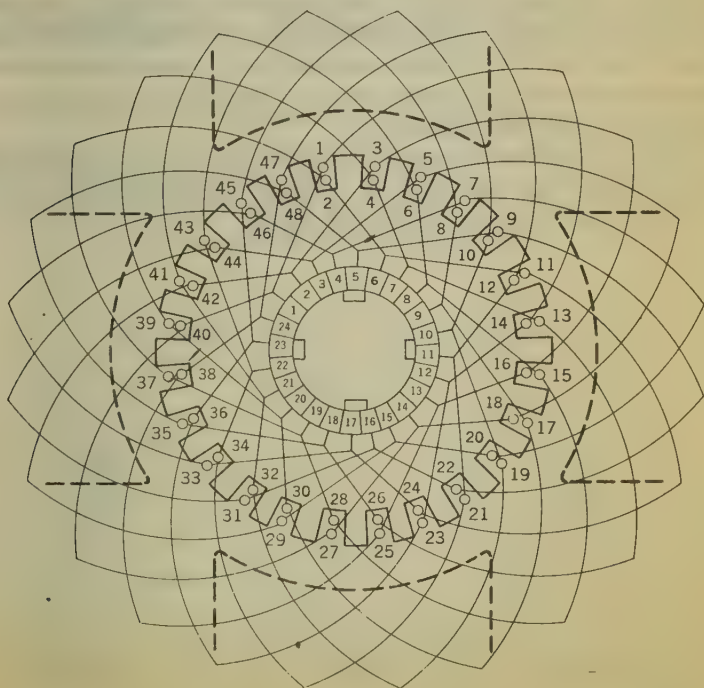


FIG. 29.—Four pole, 24 slot, wave winding.

Practically all of the important armature windings for large and moderate sized direct current machines are covered by the foregoing.

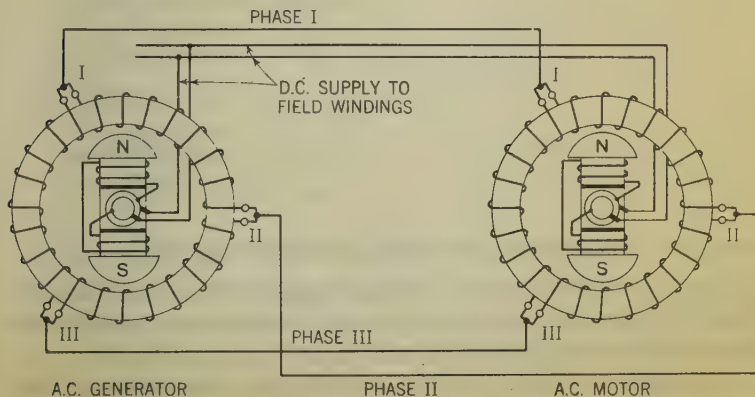
Comparison of Lap and Wave Windings.—As previously noted a wave winding has the advantage that it gives a higher voltage than the lap winding with a given number of poles and armature conductors. The wave winding is used in small machines and particularly those designed for higher voltages. To obtain a high voltage with a lap winding, the winding would result in a very large number of very small conductors. Another advantage in using the wave winding is that no equalizer connections are necessary.

When a machine is required to carry a heavy current at a low voltage, the lap winding is more satisfactory since this winding gives a larger number of paths.

CHAPTER 20

Alternating Current Armature Winding Methods

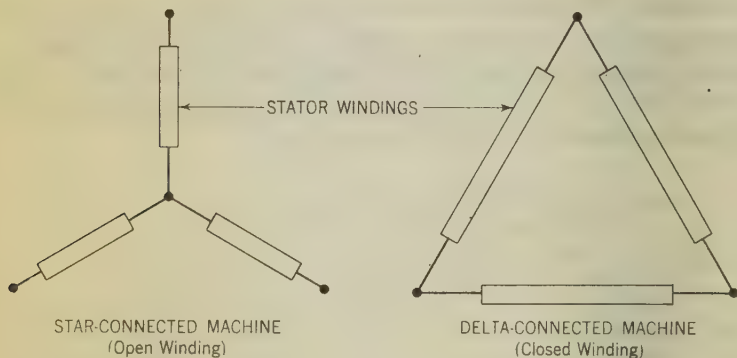
General.—The windings for alternating current motors and generators are substantially alike. Direct current and alternating current windings differ essentially in that while the former is of the *closed-circuit type*, the alternating current windings are generally of the *open-circuit type*.



FIGS. 1 AND 2.—Schematic diagram illustrating the similarity of A.C. motors and generators. Structurally the synchronous motor is often difficult to distinguish from the generator. Just as the direct-current generator is convertible without change into a direct-current motor so an alternating current generator is convertible into an alternating current motor.

The open circuit winding is one in which there is a continuous path through the wire of the coils of each phase of the winding with the ends of this path forming two free ends. Such a winding does not close upon itself.

Closed circuit windings are used only in special A.C. machines; for instance, where the machine is required to deliver a large current at a low voltage. In such a machine the winding generally consists of several similar paths connected in parallel to the terminals of the armature, in this manner forming one or more closed circuits within the armature winding.



FIGS. 3 and 4.—Showing example of an open and closed winding, respectively.

Closed circuit windings are also employed in machines required to carry both alternating current and direct current such as double current generators and rotary converters.

Alternating current windings are usually described in the number of slots per phase per pole. For example, if the armature of a 20-pole three-phase machine have 300 slots, it has 15 slots per pole or 5 slots per phase per pole, and will be

described as a five-slot winding. Therefore, in order to trace the connection of a winding, it is necessary to consider the number of slots per pole for any one phase.

Types of A.C. Windings.—A.C. windings may be classified according to the winding method employed, as:

1. Distributed windings.

(a) Chain or spiral.

(b) Lap.

(c) Wave.

2. Concentrated windings.

(a) Lap.

(b) Wave.

Windings may also be divided into:

3. Single-layer windings.

4. Two-layer windings.

In addition there are:

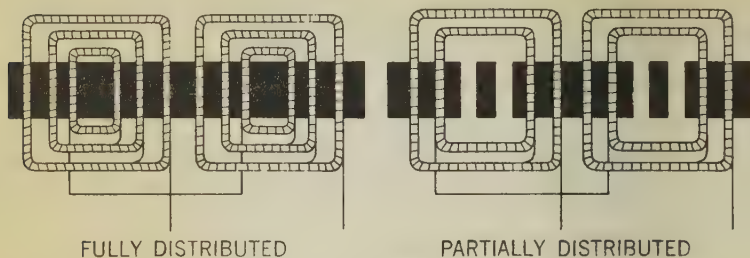
5. Half-coil.

6. Whole-coil windings.

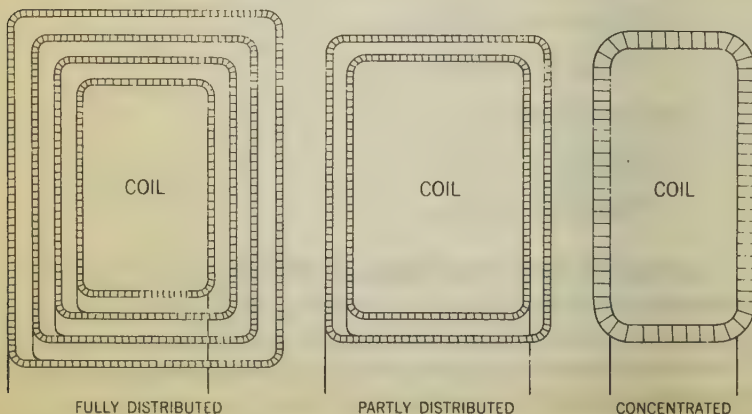
Distributed and Concentrated Windings.—A *distributed winding* may be defined as one which has its inductors of any one phase under a single pole placed in several slots, whereas a *concentrated winding* is one in which the inductors are grouped together in one slot per pole per phase.

It is customary in a distributed winding to distribute the series inductors in any one phase of the winding among two or more slots under each pole.

On the other hand, a partially distributed winding is one in which the coil slots do not occupy all of the circumference of the armature, that is, the core teeth are not continuous.



FIGS. 5 and 6.—Illustrating a fully and partially distributed winding, respectively.



FIGS. 7 to 9.—Typical coils showing difference between fully distributed, partially distributed and concentrated coil forms.

A concentrated winding has a greater armature reaction and inductance than the distributed type, hence the terminal voltage of an alternator with a concentrated winding falls off more than one with a distributed winding when the current output is increased. An A.C. generator, therefore, does not have as good regulation with a concentrated winding as with a distributed winding nor as great capacity.

A concentrated winding though giving higher voltage than the distributed type with no load, may give a lower voltage than the latter at full load.

Spiral or Chain Winding.—This type of winding is used mainly in A.C. generators and may have an odd or even number of inductors per slot, but several shapes of coils are required since the coils enclose one another.

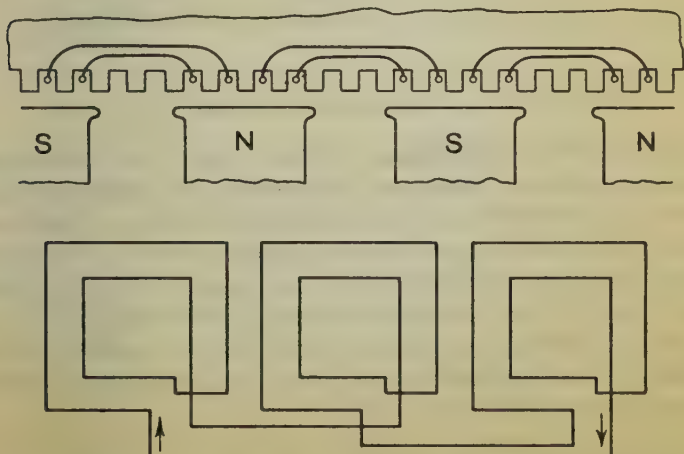


FIG. 10.—Typical single-phase, single-range spiral or chain winding.

A coil arrangement of this type, however, makes good insulation possible and is frequently employed in high voltage generators.

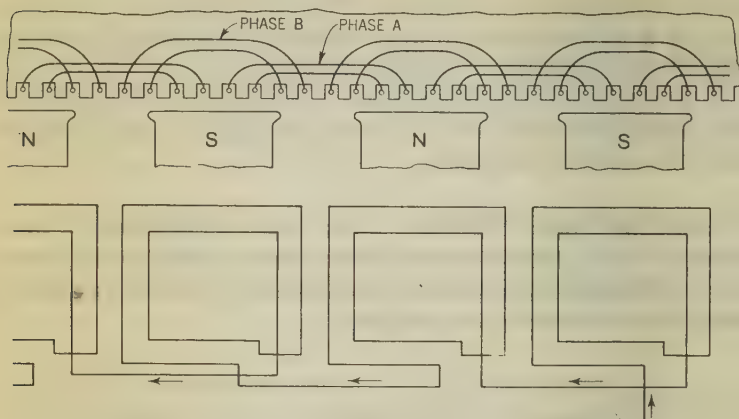


FIG. 11.—Typical two-phase, two-range, spiral or chain winding.

Lap and Wave Windings.—When applied to alternating current machines, these are principally the same as those previously described for direct current windings. There are single and double layer windings usually made up of form-wound coils. It should be noted that some of the rules which were given for D.C. machine windings, do not apply to A.C. windings. Briefly, as applied to an A.C. machine, a *lap winding* is one in which all coils in a pole group can be traced through before leaving that group.

A *wave winding* is one in which only one coil in each pole group can be traced through before leaving that group.

Also, in a D.C. machine the wave winding gives a higher voltage than a lap winding, with a certain number of coils, whereas in an A.C. machine the voltage will be the same for both wave and lap winding if the number of series connected conductors and other conditions are the same.

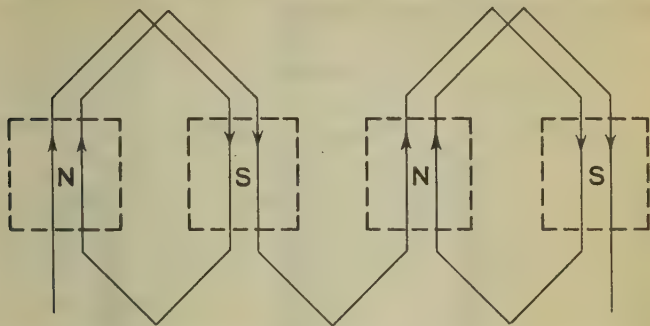


FIG. 12.—Single-phase distributed lap winding with two slots per pole, per phase and with one coil side per slot.

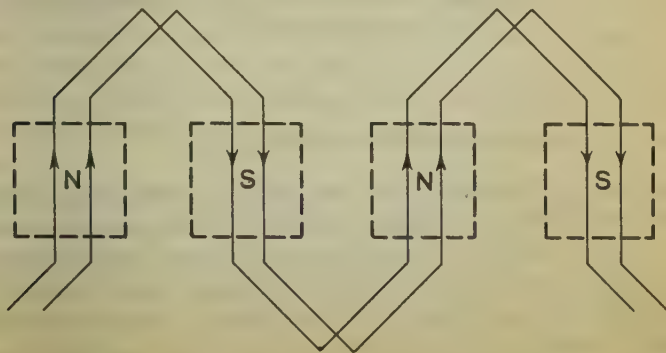


FIG. 13.—Single-phase distributed wave winding, with two slots per pole, per phase, with one coil side per slot.

The type of winding to be selected for a certain machine depends upon service and other conditions. Due to the fact that the wave winding is stronger mechanically than the lap winding, it is generally used on phase-wound rotors, as there is often considerable stress on their windings, due to centrifugal force and starting torque. Stators on the other hand are generally wound with lap windings.

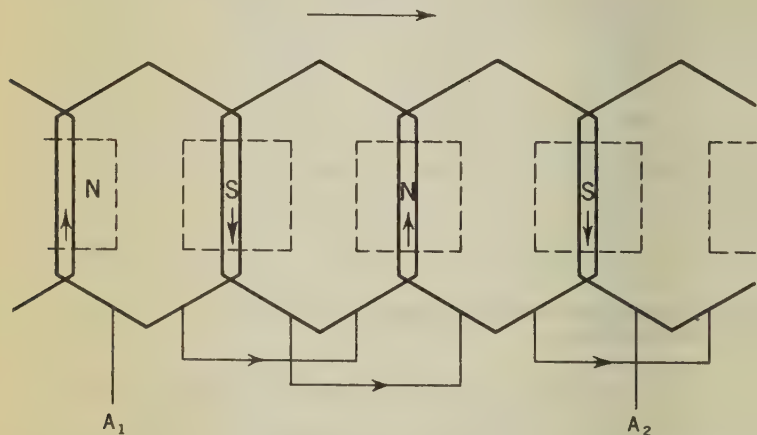


FIG. 14.—Two-layer single-phase winding with one slot per pole.

The main advantage of the double layer type is that it provides a mechanically balanced winding that is very acceptable for a wound rotor that would operate rather unsatisfactorily with a mechanically unbalanced winding, even though this unbalance was overcome by the addition of properly balanced weights which are not very satisfactory at best. Figs. 14 and 15 show a developed diagram of a two-layer lap, single- and two-phase winding, respectively.

With the winding distributed in several slots per pole per phase, it may be connected progressive or retrogressive just as in a direct current machine.

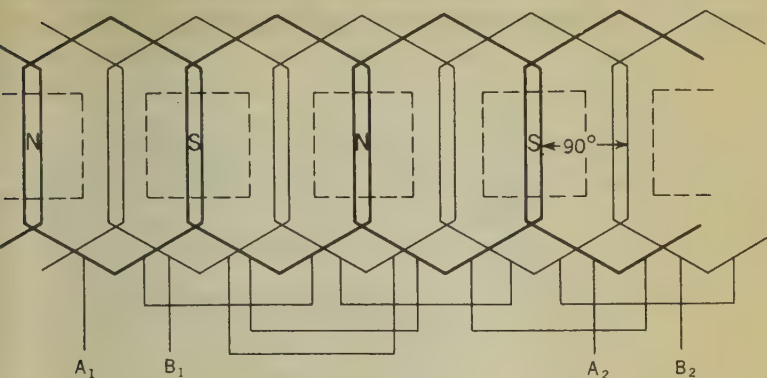


FIG. 15.—Two-layer, two-phase winding, with one slot per pole, per phase.

Whole and Half-Coiled Windings.—By definition, a whole-coiled winding is one which is connected in such a way that there are as many coils per phase as there are poles in the machine. A half-coiled winding is one in which the coils are connected so that there is only one coil per phase per pair of poles.

The difference between the two types is mainly in the method of making end connections for the coils.

In the whole coiled winding each slot contains two coil sides. In the half-coiled winding, each coil may have twice the number of turns as that of a whole coiled winding or the two coils under opposite poles of the latter type may be connected together in series and taped together to form one coil in case of a change in connection.

The advantages in employing half-coiled windings are mainly that in large generators the armature frame may be conveniently split into two sections for transport without disturbing many of the end connections. In single-phase machines, however, a half-coiled winding is nearly equivalent electrically

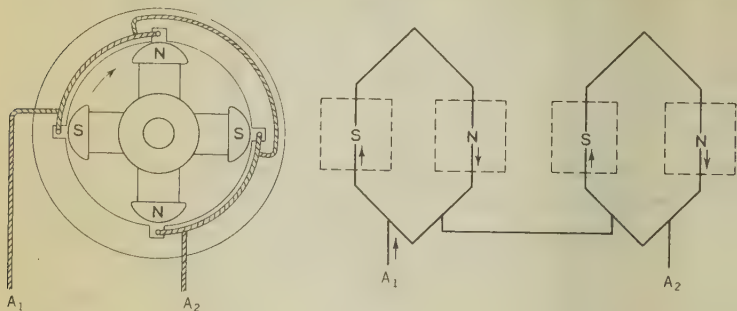


FIG. 16.—Illustrating a single-layer, half coil winding having one slot per pole.

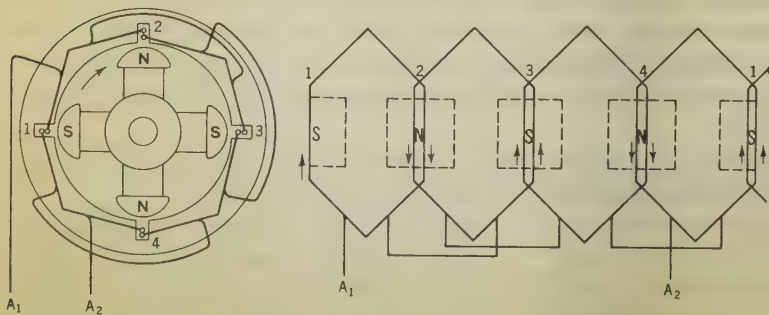


FIG. 17.—Double-layer, whole coil winding, with one slot per pole.

with a monotooth winding and is not of any particular advantage. Also the regulation and ventilation with this type of winding is poor and in addition requires more head room.

Terms and Definitions.—In order to facilitate the understanding of A.C. windings the following terms will be of assistance:

A Coil Group.—This is the number of coils for one phase for one pole. The formula for determining a coil group is:

$$\text{coils per group} = \frac{S}{P \times N} \quad (1)$$

P = number of poles.

N = number of phases.

S = number of slots.

Full Pitch and Span.—This term refers to the coils that span from a slot in one pole to a corresponding slot or position in the next pole. The formula for determining a full pitch coil span is:

$$\text{full pitch coil span}^* = \frac{S}{P} + 1 \quad (2)$$

S = number of slots.

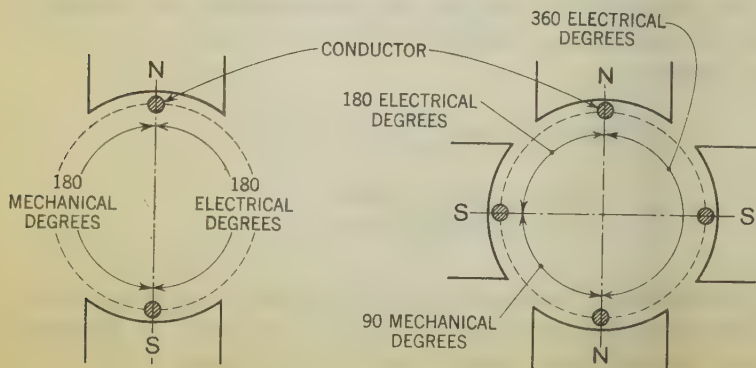
P = number of poles.

Fractional Pitch.—This term applies to windings having coils which span more or less than a full pitch. A fractional pitch should never be less than 50% of full pitch.

*NOTE.—A full pitch coil span is also known as a 100% pitch. In certain windings it may be more than a full pitch, but should never exceed 150% pitch.

Electrical Degrees.—It is a well known fact that in mechanical work a complete circle is divided into degrees and parts thereof. Thus, one degree is usually defined as a $1/360$ th part of the circumference.

In electrical machinery, and winding work, however, this may not be necessarily true. *The manner of designating electrical degrees is such that the distance between the centers of two like poles is taken as 360 electrical degrees.* With this definition in mind, it will be comparatively easy to arrive at the number of electrical degrees in any machine, irrespective of the number of poles involved. Figs. 18 and 19 show the number of electrical degrees for a two and a four pole machine respectively. Thus, a bipolar machine contains 360 electrical degrees, a four pole machine 720 electrical degrees, and a six pole machine will have 3×360 or 1,080 electrical degrees. An eight pole machine on the other hand would have 4×360 or 1,440 electrical degrees, etc.



FIGS. 18 AND 19.—Illustrating how electrical degrees differ from mechanical degrees in electrical machinery.

Electrical Degrees per Slot.—This term is generally employed to express the portion of the pole which one slot covers. The formulae for determining the electrical degrees per slot is:

$$\theta = \frac{180 \times P}{S} \quad (3)$$

Where θ = electrical degrees per slot.

P = number of poles.

S = number of slots.

Voltage Formulae.—A volt is a unit of potential and is defined as the voltage induced by the cutting of 10^8 lines of force per second. In the operation of an A.C. generator the maximum voltage generated may be expressed by the following formulae:

$$E_{max} = \frac{\pi \times f \times Z \times \phi}{10^8} \text{ volts} \quad (4)$$

Where E = volts.

f = frequency.

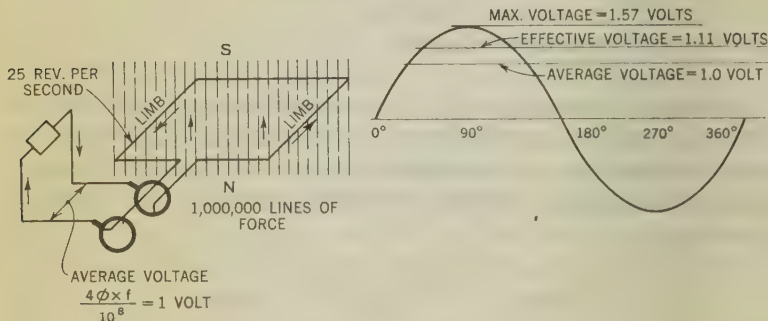
Z = number of inductors in series in any one magnetic circuit.

ϕ = magnetic flux, or total number of magnetic lines in one pole or one magnetic circuit.

The maximum value of voltage as expressed in equation (4) occurs when $\phi = 90^\circ$, but since the effective voltage value E_{eff} is equal to the maximum voltage divided by $\sqrt{2}$ a substitution in formula (4) gives:

$$E_{eff} = \frac{\frac{1}{2}\sqrt{2} \times \pi \times f \times Z \times \phi}{10^8} = \frac{2.22 f \times Z \times \phi}{10^8} \text{ volts} \quad (5)$$

This is usually taken as the fundamental formula in designing A.C. generators. It should be noted that it is deduced on the assumption that the distribution of the magnetic flux follows a *sine law*, and that the whole of the loops of active inductors in the armature circuit act simultaneously, that is, the winding is concentrated.



FIGS. 20 and 21.—Elementary A.C. generator developing one average volt. If the loop makes one revolution per second and the maximum number of lines of force embraced by the loop in the position shown (the zero position) be denoted by ϕ , then each line will cut (2ϕ) lines per second, because it cuts every line during the right sweep and again during the left sweep. Hence each line develops an average potential of (2ϕ) units (C.G.S.) and as both links are connected in series, the total potential is (4ϕ) units per revolution. Now if the loop makes (f) revolutions per second instead of only one, then (f) times as many lines will be cut per second and the average potential will be $(4\phi f)$ units. Since the C.G.S. units of potential is so extremely small, a much greater unit called the volt is used, which is equal to 10^8 C.G.S. units. Therefore, average potential = $4\phi f/10^8$ volts. The value of ϕ in actual machines is very high, being several million lines of force. The illustration shows one set of conditions necessary to generate one average volt. The maximum potential developed is $1/0.637 = 1.57$ volts. The effective potential being 1.57×0.707 or 1.11 volts.

Winding Co-efficient.—In actual winding practice, the coils are more or less distributed, that is, they do not always subtend an exact pole pitch; moreover, the flux distribution which depends upon the shaping and breadth of the poles is quite often

different from a sine wave distribution. Therefore, the co-efficient 2.22 in equation (5) is often departed from and in a general case this equation may be written:

$$E_{eff} = \frac{KfZ\phi}{10^8} \text{ volts} \quad (6)$$

Where K is a number which may have different values according to the construction of the generator.

The value of K is further influenced by a *breadth coefficient* or *spread* or *span factor*.

Spread Factor.—In order to minimize the voltage impedance and to improve the regulation, the coils in the various phases of an alternating current machine armature are divided up over a number of slots, instead of being concentrated all in one slot. As a result of this, the voltages in the various coils are not all in phase, and the resultant voltage is not the arithmetical sum of the voltage in the several coils. To correct for this, a factor known as the spread factor is introduced into voltage calculations.

Slots per phase per pole	Spread Factor		
	Single phase	Two phase	Three phase
1	1.000	1.000	1.000
2	.707	.924	.966
3	.663	.911	.960
4	.653	.906	.958
6	.644	.903	.956

FIG. 22.—Table showing spread factor of single, two- and three-phase windings for various numbers of slots and coils per pole.

For practical estimation this reduction factor may be taken as 0.96 in the case of a distributed three-phase winding; 0.90 for a distributed two-phase winding; and 0.84 for a single-phase winding distributed over two-thirds of the pole pitch.

A table giving the values of the spread factor is given herewith and is based upon the same number of inductors being placed in each of the slots and all of the slots being used.

Chord Factor.—If fractional pitch is used, a *chord* or *pitch factor* must in addition be introduced into our voltage formula. This factor is similar to the previously discussed breadth factor and will further reduce the voltage obtained. Fig. 23 shows a curve of such chord factors. It will be noted that the factor depends solely on the percentage of 180° of full coil span that the coil sides are spaced.

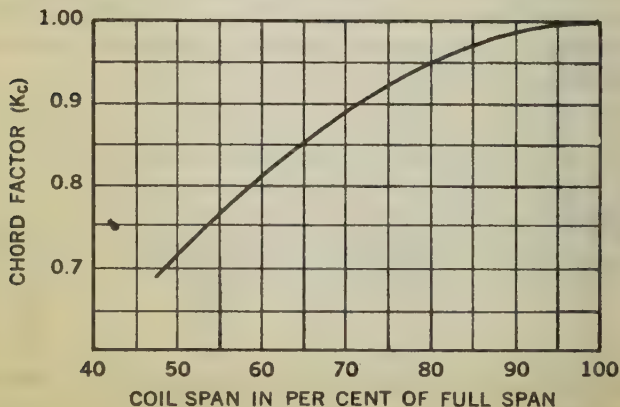


FIG. 23.—Curve showing *chord factors* of stator windings.

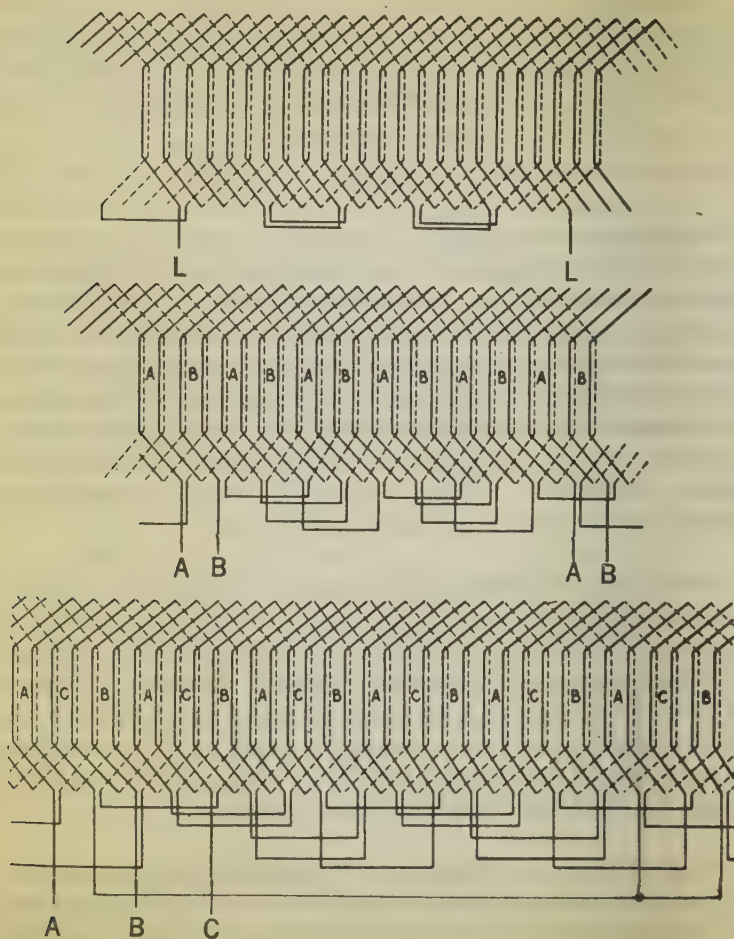
Therefore, in order to obtain an absolute value for the voltage generated in a given winding, it will be necessary to multiply formula (6) with the two factors; spread factor (K_s) and chording factor (K_c). The complete formula may then be written as:

$$E_{eff} = \frac{2.22 K_s K_c Z f \phi}{10^8} \text{ volts} \quad (7)$$

Single-Layer Winding.—As the name implies, it is only one layer to the winding of any one phase, that is, the windings of any one phase do not lap over one another. This type of winding is used mainly in high voltage machines where good insulation between the coils is of the utmost importance. With the chain method of winding, the conductors of the coil are concentrated in a small bundle which is thoroughly insulated, and which when installed has sufficient room around it for proper ventilation. Figs. 10 and 11 show a single layer, single- and two-phase winding, respectively.

Two-Layer Windings.—Although the cooling (ventilation) and insulating qualities of this type of winding is not as good as the chain winding, it is more generally used than the chain winding, because only one shape of coil is necessary. Because of this, the winding is more economical and easy to install, and its insulating qualities are ample for moderately low voltages. Figs. 24 to 26 illustrates a two-layer, single-, two- and three-phase lap-connected winding, respectively.

Single-Phase Lap Winding and Method of Representation.—It has been previously pointed out that winding diagrams may be represented in various ways, although the most common method of illustrations are usually either by means of a radial or extended view or by means of the developed type.



FIGS. 24 TO 26.—Double layer, lap connected, single, two- and three-phase star connected windings, respectively.

The following will help to illustrate the various methods of representation of the winding circuit of a single-phase lap winding, as shown in figs. 27 to 31.

Fig. 27 shows a radial view of the single-phase lap winding. It will be observed upon tracing through the winding that the coils are so connected that they are alternately north and south in exactly the same manner as field coils of direct current machines. It should be noted that there are two coils per group.

Fig. 28 represents a circle line diagram of the winding where each of the small circular arcs represent a group. The manner in which these groups are connected together are clearly shown in the figure, the small arrows indicating the direction in which the winding progresses through the group, that is, right to left or left to right, as the case may be.

Again a straight line diagram of the winding is shown in fig. 29. This bears the same relation to the developed diagram, that the circle line diagram, bears to the radial view diagram.

Fig. 30 shows a developed diagram of this same winding. Here the coils are shown on a flat surface exactly as if they had been placed on the outside of a cylinder and split through the side and rolled out.

Each of these diagrams shows the manner in which the coil groups are connected together and are all employed to some degree depending upon the particular machine and type of winding used. The circle line diagram is perhaps the most accurate because it shows the groups as they are actually laid out while the straight line form of diagram does not. Thus, fig. 28 shows coil group 4 right next to 1, whereas fig. 30 shows coil group 4 at one extreme end and 1 at the other.

Although they are both correct, fig. 30 requires the use of imagination in order to obtain the actual condition, while fig. 28 requires no such effort.

Fig. 31 shows a circle line diagram of the same winding, that is essentially the same as that of fig. 28, except for the fact that coil group 1 is connected to coil group 3, and group 3 is connected by the reversing jumper *X* to group 4, and thence across to group 2.

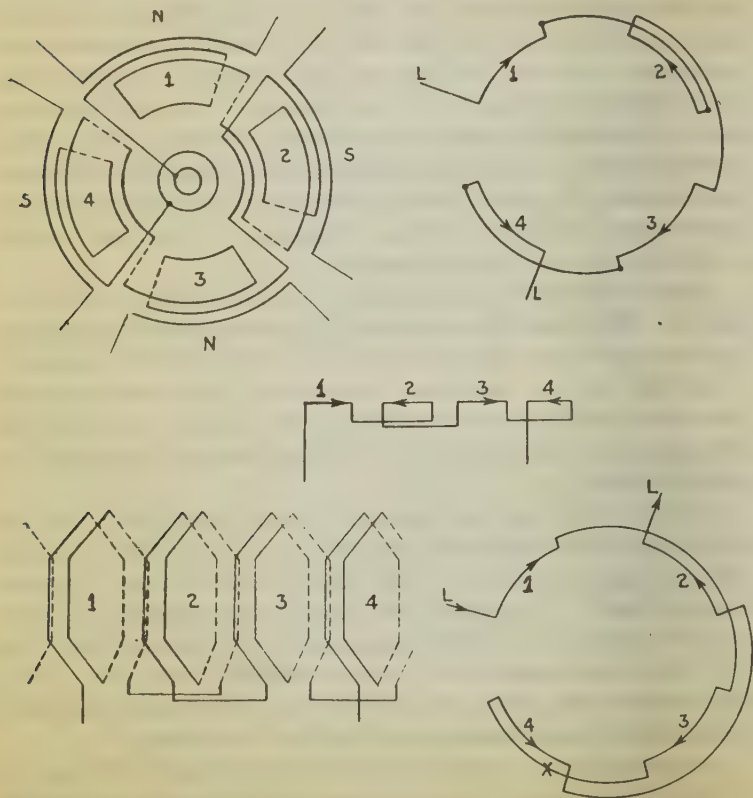


FIG. 27 to 31.—Showing a typical single-phase winding and various methods of representation.

It will be observed that whenever possible a group between connecting points has been skipped. Thus 2 was skipped to get to 3, but 3 is connected to 4 in order to maintain the series connection, then 3 is skipped in going from 4 to 2.

Long and Short Jumpers.—The type of winding shown in fig. 31 is called a *long jumper* winding in contrast to fig. 28, which is called a *short jumper* winding. Without further consideration, it may seem to be an unnecessary lot of trouble in connecting a machine long-jumper, but there are several reasons for employing this connection.

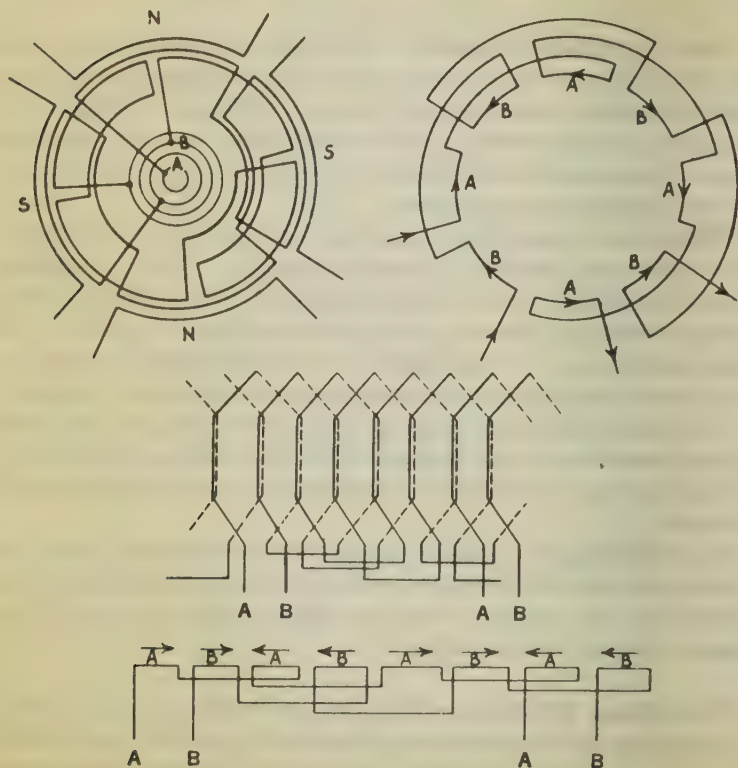
When short jumpers are employed, the leads from the groups may be left long enough to serve as jumpers. Thus, a smaller number of soldered joints will be obtained. In all multi-speed motor windings, however, long jumpers must be used. In large machines, or in machines with a large number of coils in each group, long jumpers are too long and should not be used.

In a single connection such as that shown in fig. 31, the long jumper would not be of any particular advantage, except that it would permit laying the jumpers down in a more symmetrical manner.

On multi-circuit machines this connection is very useful in preventing internal circulating currents due to variations in the depths of the air-gap resulting from slight manufacturing defects or from bearing wear.

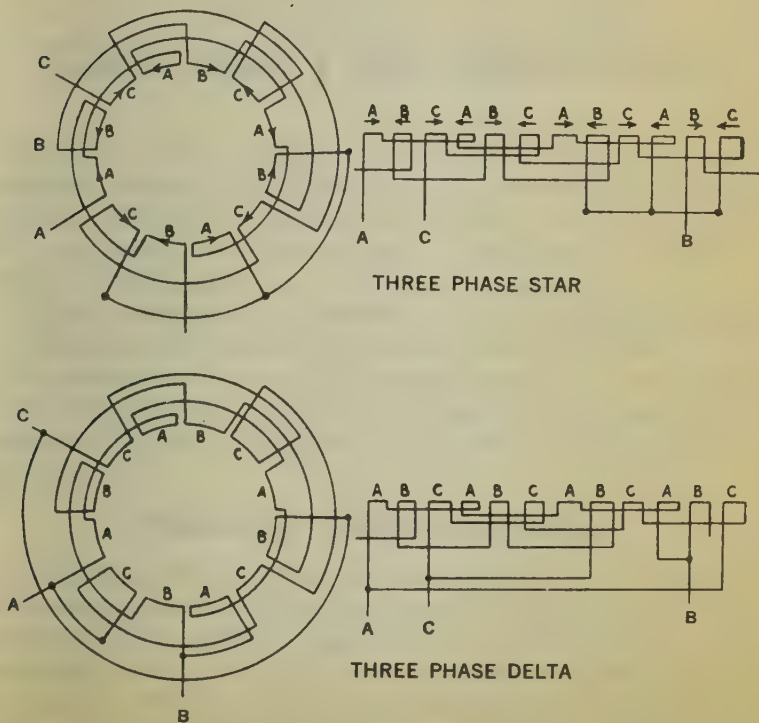
Two-Phase Windings.—This type of winding can be made from any single-phase winding by providing another set of slots displaced along the surface of the armature to the extent of one-half the pole pitch placing therein a duplicate winding. A single-circuit four-pole two-phase winding is shown in figs. 32

to 35. There are numerous kinds of two-phase windings, the coils may be concentrated or distributed, half or whole coil, etc.



FIGS. 32 TO 35.—Showing typical four pole two-phase winding and various methods of representation.

Three-Phase Windings.—On the same general principles applied to two-phase windings, a three-phase winding can be made from any single-phase winding by placing three identical single-phase windings spaced out successively along the surface of the armature at intervals equal to one-third and two-thirds,



FIGS. 36 to 39.—Showing a star- and delta-connected winding, respectively.

respectively, of the double pole pitch, the unit in terms of which the spacing is expressed being that pitch which corresponds to one whole cycle. Figs. 36 and 37 show a three-phase star and delta connected winding, respectively.

CHAPTER 21

Coils and Their Insulation

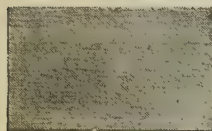
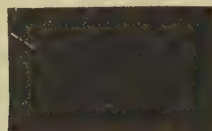
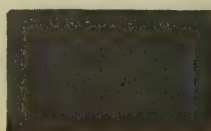
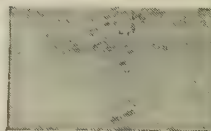
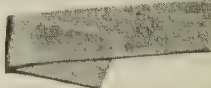
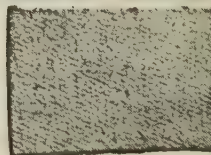
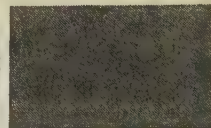
General.—The insulation of coils in electrical machinery performs two functions, namely, to provide mechanical protection and to serve as electrical insulation. The material used for mechanical protection consists of pressboard, presspahn, hard and vulcanized fiber, fish paper, rope paper, etc.

Material used for high temperature and electrical insulation consists of mica, micarta, mica paper, mica cloth, etc.

Materials used for electrical insulation only are, cotton tape and oiled or treated cloth which includes cotton or linen muslin, varnished cambric, varnished muslin, empire cloth, asbestos, glass, etc.

Material Characteristics

Asbestos.—For electrical insulating purposes this material is generally used in the form of asbestos paper or paper tape, asbestos mill board or asbestos lumber. In such forms it may contain from 10% to 20% of wood pulp and glue to give it strength. The scrysotile asbestos may be spun and made into asbestos cloth or cloth tape, which generally contains approximately 14% of cotton. Selected long fiber material is made into 100% asbestos twine.

Molding Mica
PlateFlexible
Mica PlateAsbestos
SheetCloth-backed
Mica TapeGlass
TapeFishpaper
and Mica
WrapperBlack Varnished
Cambric TapeSegment
Mica PlateTan Varnished
Cambric TapeJap Paper
and
Mica TapeCotton
TapeAsbestos
Cloth

Fullerboard



Fishpaper

Figs. 1 to 14.—Showing various insulating material usually employed in insulation of windings. (Courtesy Westinghouse Electric & Mfg. Co.)

Asbestos is very poor electrical insulation, but an excellent vehicle for insulating compounds. When dry and properly treated, it is valuable for high temperature insulating applications and for dissipation of corona in high voltage apparatus. Furthermore, it is one of the few fabrics that termites will not destroy.

Glass.—Until recently this material has not been considered an electrical insulation. Now, however, glass is being spun or woven into fabrics that have some very excellent insulating properties.

Mica.—This is mined in the form of large crystals, which split readily into thin, tough, parallel-sided laminae or flakes. Mica is probably the most valuable insulating material in general use. It is used as an electrical insulation not only in windings, but in almost every electrical apparatus.

In windings, it is used particularly on the larger alternating current machines, and also for direct current armatures and in commutators and also as flash guards between the commutators and the armature winding of large units.

The two kinds most generally used for insulating purposes are:

1. Muscovite, usually called white or India mica.
2. Phlogopite, generally called amber mica.

It is manufactured in sheets, blocks and tubes.

Cotton.—Like all other organic materials, cotton is not suitable for high temperature applications which the inorganic materials described will withstand satisfactorily, yet the uses of cotton for electrical insulation are many and diversified.

Cotton, in the form of fabrics, is extensively used for electrical insulation. These fabrics are generally processed with various varnishes, compounds or gums. Some of these composite materials have remarkably valuable insulating properties.

Cotton Fabrics.—Untreated materials are used extensively for oil type transformer insulation. They are thoroughly dry when immersed in the oil, which quickly impregnates all fibers. The result is an insulating material having excellent physical and dielectric properties.

Treated (or what might be termed “pre-treated”) fabrics are the fundamental Class A insulating materials. There are many varieties of these treated fabrics. The two most commonly used are:

1. Tan-linseed oil or tung oil varnish-treated cloths.
2. Black-varnish and asphaltum or bitumen, compound-treated cloths.

When tested in sheet form between 2 in. electrodes the instantaneous breakdown voltage of the tan varnished cloths will generally be not less than 1,000 volts per mil, and the black cloths 1,200 volts per mil. The other dielectric properties of these materials are very good.

Adhesive or Friction Tape.—This insulating material, which is a cotton fabric treated with a viscous rubber or bitumen compound, is used very little as electrical apparatus insulation, except on the coil end connections of low voltage induction motors, where it is thoroughly covered with shellac or varnish. When “fresh” and in good condition, it may have a dielectric strength of approximately 100 volts per mil, but it deteriorates very quickly when exposed to air.

Paper.—Many varieties of paper are used in insulating electrical apparatus. These range from the very thin Japanese tissues, through the cotton rag, the Manila (hemp) the Kraft (wood pulp) and the jute (used principally in making fiber) to the thickest fish paper and fullerboard types. Because of an extreme tendency to absorb moisture, untreated papers have little insulating value. Papers treated or impregnated with oils, varnishes, or compounds may have high dielectric strength and other valuable insulating properties. Tuffernell is a new development in insulated round magnet wire consisting of a layer of very high grade paper bonded or cemented over a very high grade enameled wire.

It has more than 50% greater dielectric strength than other insulated wires.

The over-all size of the insulated conductor is smaller than with conventional insulation. Therefore, it enters the slots easier and permits the use of more copper in a given slot area.

Shellac.—It is one of the oldest insulating materials, and is still one of the natural gums most commonly used in the electrical industry.

Orange shellac, which is generally used for insulating purposes, has a dielectric strength of 450 to 580 volts per mil. It has extremely high insulation resistance and low dielectric loss, or power factor. Although shellac dries with a hard, tough film, it is very brittle. The melting point increases after each melting until after prolonged heating it becomes more or less infusible. The moisture resistance of shellac is low and consequently it is affected by climatic conditions.

Shellac is an excellent binder for mica and other solid insulation as it has particularly good adhesive properties.

Varnishes.—Insulating varnishes are of great importance in the electrical industry and particularly in the maintenance of electrical apparatus. An insulating varnish is a chemical compound of varnish gums and drying oils, having high dielectric strength and other properties that afford protection to the windings of electrical apparatus.

Insulating varnishes are compounded to meet specific applications. The varnish best suited for treating armature coils would not be satisfactory for oil-immersed transformers. Clear varnishes, in general, are not as moisture-resisting or acid-resisting as the blacks. They are oil-resisting, however.

Baking varnishes are usually applied by the dipping or the vacuum process. When facilities for such operations are not available, the varnish may be brushed or sprayed on the insulation. Unless the windings have been previously well filled with varnish or compounds, the brushing or spraying method is likely to be much less satisfactory than the dipping process. The usual baking temperature is from 110° to 135° C. The baking time will vary from six hours to forty-eight hours, or even longer, depending on the size of the apparatus.

An important function of an air-drying varnish is to produce a surface coating of high dielectric strength and good appearance. Such varnishes are usually applied by the spray method.

Thermoset Varnish.—In recent years, synthetic resins have been used extensively in varnish manufacture. The phenol-formaldehyde series are representative of the heat-hardening resins, and varnishes containing them are heat-hardening or thermo-setting. They will cure by heating alone and do not require oxygen. Certain other resins used in varnishes are thermo-plastic and will resoften when heated, although some of these will set after continued heating.

Micarta.—This is made of layers of cloth, paper or wood, saturated with either a synthetic or organic resin, and then compressed under heat; this makes the resin permanently hard, and the Micarta will never thereafter be softened by heat, pressure or solvents. It was as an insulator that Micarta was developed and today has innumerable applications as such.

While most good insulating materials are mechanically weak, Micarta is the equivalent of a “metal” that is non-magnetic and also an insulator. It is strong, tough, rigid, and is readily machined from rod or plate stock. Molded pieces of intricate shape are also obtainable. Harder and stronger than wood, it will not readily split or break, even from a violent blow.

Most of the grades absorb very little moisture, and are not affected by moderate strength acid solutions.

A few Micarta applications in electrical equipment are insulating washers, controller panels, controller cams, tubing, brush rigging, bus bar supports, insulating barriers, spools for magnet coils, and transformer insulation.

Coil Taping Practice

Materials.—The materials used in making armature and stator coils are: (1) *Copper*, (2) *Insulating Tape*, and (3) *Varnish*. To insure getting as perfect materials as possible, rigid specifications must be adhered to in addition to careful checks both as to the type of material selected and as to its quality.

Important items to watch in using copper, tape and varnish may be briefly summarized as follows:

Copper (the Electrical Conductor.)

1. It must be kept clean and free of dirt, grease or oil. If necessary, wipe it clean before taping.
2. It must be absolutely free of slivers, burrs, fins, and solder beads. Use fine sand paper to smooth conductor surface defects and then wipe clean of copper dust, etc.
3. Check edges of wire or copper conductor to see that they are well rounded. *Never apply tape over sharp edges.*
4. It must be kept straight as shaped in coil form. Avoid unnecessary twisting, bending or kinking.
5. Watch for tears, breaks, skips or holes in wire that has been insulated. Repair such defects as directed.

Tape (Varnished Cambric, Staybinding or Mica—the Electrical Insulator).

1. Check the tape for thickness and type. In varnished cambric taping both the 0.005 in. and the 0.007 in. tape are black and special precautions must be taken to keep them apart.
2. Check the tape for flaws while applying. This is especially essential when applying mica tape. *Never* apply mica tape from which the mica has been pulled out or flaked.
3. Do not allow tape to drag or drop on floor. It may pick up dirt, metal chips, etc.

Varnish or Compound.—This is the bonding or filling agent in coils which also act as a lubricant in taping and facilitates tight taping.

1. A check should be made to insure the correct grade of

varnish and its gravity. If varnish thickens during the application process, it should be thinned according to specifications or under the foreman's directions.

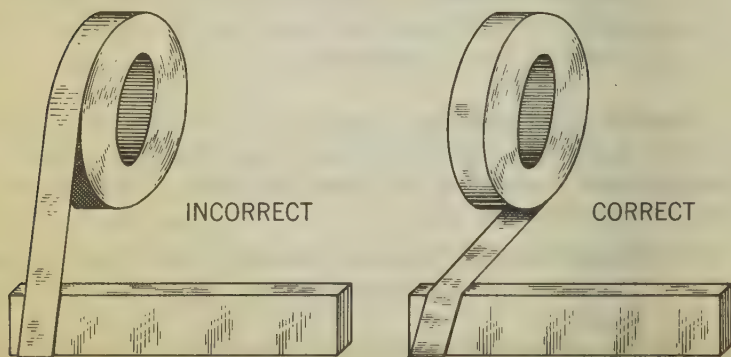
2. Never allow dirt or foreign particles to get into the varnish.
3. Keep varnish containers covered when not in use.
4. Containers with #31 Coil Sticking Varnish and with #36 Gilsonite Varnish are to be emptied and cleaned at the end of each day. *Use black containers for #31 and yellow containers for #36.* #36 Gilsonite varnish is the thicker of the two and is used only on the slot portion in conductor taping. #31 Sticker is used on the end portion in conductor taping and on both the slot and end portions in coil taping.
5. Paint brushes must be kept in good condition. Never use a stiff, hard brush as it will not spread varnish uniformly and may damage the tape. When it becomes necessary to soften a brush used for shellac, soak it in alcohol; to soften a brush used for #31 Sticker or #36 Gilsonite, soak it in naphtha.

Material Conservation.—Since all of the materials which go into a coil are costly, and at times difficult to obtain, it goes without saying: *Do Not Waste Materials.* Ways to aid in material conservation are:

1. Watch scrap at start and finish of roll of mica tape. Do not scrap good material at each end, just the "lead" paper.
2. Do not discard the end of the roll of tape just because it is inconvenient to use.
3. Use reclaimed tape or stripping tape to pad rollers and bench arms.

4. Do not waste varnish.
5. Do not discard a roll of mica or varnished cambric tape if it is too dry or stiff to use. Return it to the store-room where it can be reclaimed. Call the supervisor's attention to dry or stiff tape.
6. Remember above all things that while it is very important to conserve, it must not be done by using inferior materials. Materials that go into coil construction must be first class or the coils will be of no value.

Position of Roll During Taping.—Fig. 16 illustrates the correct position of the roll when starting. This position makes it easier to maintain a tight layer of tape and makes possible more convenient handling. Tape must be kept tight or wrinkles will develop which may cause defective insulation.



FIGS. 15 and 16.—Showing incorrect and correct position of tape roll when commencing the taping.

Varnish and Tape Application.—Before applying tape to a conductor or coil, a complete and thorough coating of varnish must be spread over the surface of that conductor. The same procedure must be followed after each layer of tape has been applied before another layer is wound about the conductor.

It is very important that the varnish be applied *uniformly over the entire surface* in order to obtain satisfactory bonding of tape and filling of voids. Do not paint a conductor or coil so far ahead of taping that the varnish dries appreciably before the application of the tape. Undried varnish lubricates the surface of the conductor or coil and aids in tightening the tape.

Tape.—To prevent tape from slipping at the start of a layer, lap the end under the first turn. When ending a layer, lap over the last turn only sufficiently to completely cover exposed parts, or start; and lap, sew, or glue the end in position as the supervisor directs. At both the start and finish of a layer of tape, special care must be taken to prevent excessive build-up of insulation by unnecessary lapping.

Tape must be applied uniformly tight, smooth, and wrinkle free. Tighten the tape after every 3 or 4 turns in order to insure uniform tightness.

Keep accurate count of number of layers of tape applied.

When taping with black mica tape, it is advisable to cover the hands with a *very thin film* of petrolatum or vaseline. This prevents undue sticking of varnish and aids in cleaning the hands. It is very important, however, that a very minimum of this petrolatum or vaseline get on the coil as it reduces the bonding ability of the varnish and thus produces soft spongy insulation. If, by accident, some does get on the coil, it should be carefully wiped off.

Petrolatum or vaseline may be used on hands only when taping with black mica tape.

Spread Taping.—Spread taping is used primarily to bind strands or conductors together. Therefore, this taping must be applied tightly and every effort must be made to tie strands or conductors firmly to eliminate spring.

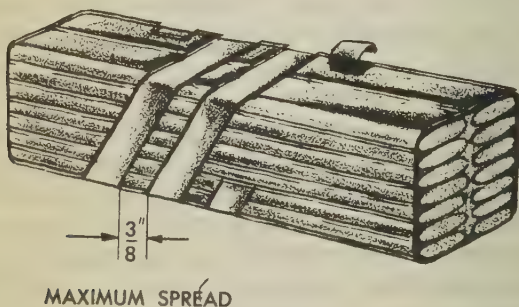


FIG. 17.—Showing maximum spread in spread taping.

The distance between each turn of tape may vary, but it should not be greater than $\frac{3}{8}$ in.

Butt Taping.—This is used primarily for the outer finishing layer of tape. It is essential that the tolerance shown in fig. 18 be maintained.

In butt taping, the edges of the tape lie tightly against each other in every turn. A slight tolerance of $\frac{1}{32}$ in. opening is allowed, but that is the maximum.

If the tape is lapped, it will build up the overall coil dimensions and produce non-uniform coil appearance. It may also cause "hot press" and "winding" trouble.

If the spread between the turns of the tape is too great, it will not afford complete mechanical protection to the insulation underneath, appearance of the coil will be non-uniform and on asbestos taping, may produce electrical shielding difficulties.

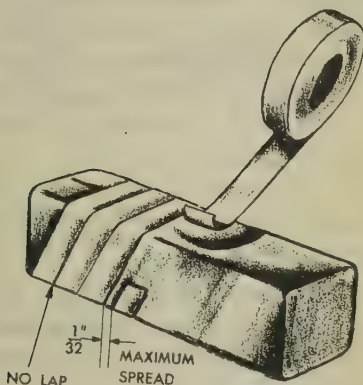


FIG. 18.—Illustrating maximum spread in butt taping.

Half Lap Taping.—All insulating tape on stator and armature coils is applied half lap. It is essential that the application tolerances shown are not exceeded. Fig. 19 illustrates half-lapping and the recommended tolerances.

The maximum tolerance for any width tape is determined by multiplying the width of tape by $\frac{1}{8}$. Thus, for 1 in. wide tape the maximum tolerance would be $\frac{1}{8}$ in. for $\frac{1}{2}$ in. wide

tape the maximum would be $\frac{1}{16}$ in.

The formula may be set up as follows:

$$\frac{1}{8} \times (\text{width of tape}) = \text{Maximum tolerance.}$$

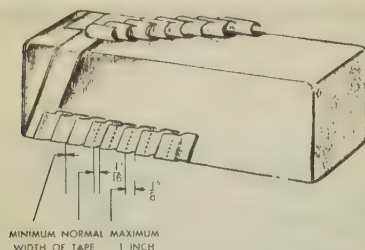


FIG. 19.—Showing *minimum normal* and *maximum* recommended tolerances in half lap taping.

Overlapping.—Sometimes the tape laps too much of the previous turn, thereby giving three thicknesses of tape instead of two. This is called overlapping. It is illustrated in fig. 20.

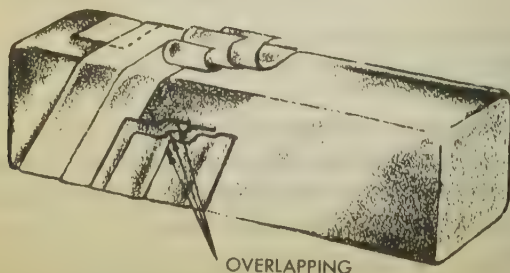
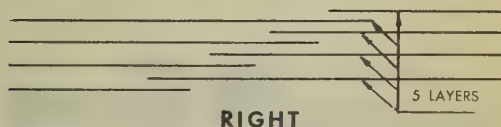


FIG. 20.—Illustrating tape overlapping.

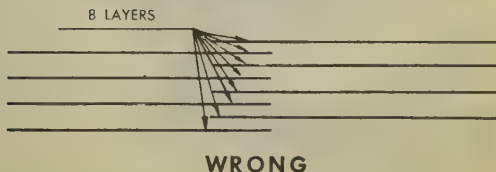
If tape is overlapped, the coil increases in dimensions, and difficulty arises in both pressing and winding. It may even be possible to hot press and wind the coil, but the mechanical effort necessary may damage the insulation, and an electrical breakdown may result.

Staggering of Splices.—It is very important to stagger splices between tapes of different sizes or kinds from one layer to the next. It is also important to stagger the start and finish of each layer of tape with respect to its adjacent layer.

Staggering of splices, starts and finishes prevents excessive build-up of material and increases both the electrical and mechanical strength of the joint.



MINIMUM BUILD-UP-GOOD MECHANICALLY
AND ELECTRICALLY



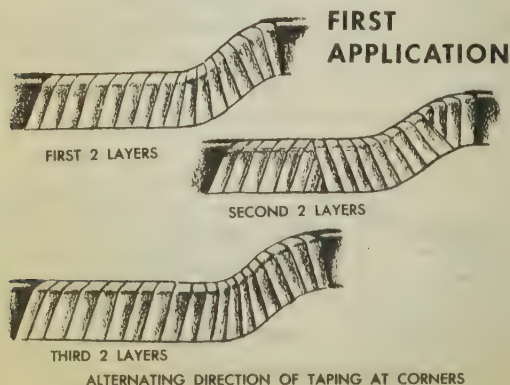
EXCESSIVE BUILD-UP-WEAK MECHANICALLY
AND ELECTRICALLY

FIGS. 21 and 22.—Showing correctly and incorrectly staggered tape splices.

The supervisor should be consulted regarding the correct spacing between splices, starts and finishes. Figs. 21 and 22 illustrates 4 layers of tape and shows that incorrectly staggered splices result in build-up of 8 layers, while correctly staggered splices build-up to only 5 layers.

Taping of Corners at Ends of Slot Portion.—The application of tape to corners at the ends of the slot portion must be watched very closely to avoid excessive build-up and yet maintain good electrical and mechanical strength.

Figs. 23 to 28 illustrate reversing the direction on high voltage stator coils having many layers of mica tape. Direction of taping at the corners is to be reversed every 2 or 3 layers. Alternating the direction of taping every 2 or 3 layers is to be carried from each application to the next, as shown.

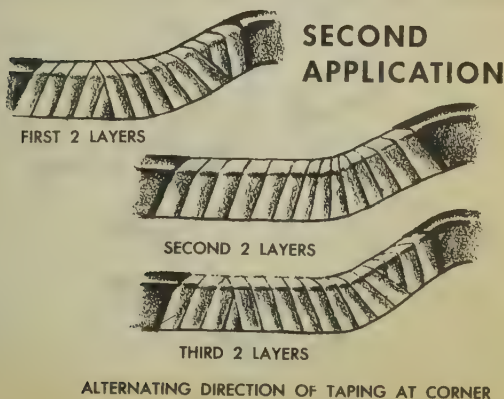


FIGS. 23 to 25.—Illustrating how a reversal in the direction of taping is made in the first application of mica tape.

In taping corners of this type, $\frac{5}{8}$ in. wide tape is usually used. Care must be taken that the splices between the narrow tape on the corners and the wider tape on the slot portion are staggered so that they are not directly above each other.

While figs. 23 to 28 are intended to illustrate reversal of direction in taping, they also bring out several other important points regarding the application of tape to corners.

1. It will usually be necessary to overlap tape slightly on the inside of the corners. However, unnecessary overlap and build-up should be avoided.
2. To aid in obtaining uniformly tight corner insulation having the correct lap, it is sometimes permissible to trim the width of the tape on the inside of the corner.

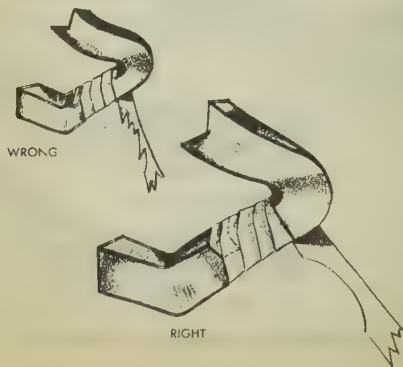


FIGS. 26 to 28.—Illustrating how a reversal in the direction of taping is made in the second application of mica tape.

Trimming width of tape in applying corner insulation is permitted only on black mica tape when used on armature coils and on conductor taping on stator coils. Silk mica tape, varnished cambric tape, and black mica tape for stator coil insulation must not be trimmed in width when taping around corners at the ends of slot portion of any type coil unless authorized by the supervisor.

3. On large stator coils such as one turn turbo coils, it is shop practice to place them on the bench or table in the reverse position shown so as to make the large corner radius more readily accessible for taping.

Taping the Knob.—In taping the knob it is permissible to cut $\frac{1}{8}$ the width of tape as shown in figs. 29 and 30 in order to avoid excessive build-up of material on the inside radius. Care must be exercised to cut the tape properly to provide suitable lapping both on the inside and outside of the knob.

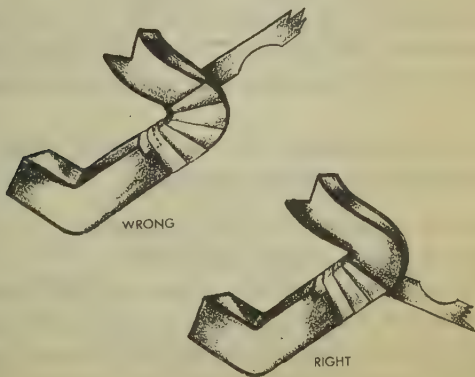


FIGS. 29 and 30.—Method of cutting side of the tape when applying only a few layers of tape to a knob.

The cut in width of tape must be smooth and continuous without ragged edges.

It should also be noted that figs. 29 and 30 illustrate the side of tape to be cut when applying *only a few layers* of tape such as is applied on low voltage varnished cambric taped stator coils. The tape is cut on the side shown in order to facilitate inspection.

When applying *a large number of layers* of either varnished cambric or mica tape to a knob, the tape should be cut as shown in figs. 31 and 32. This enables the cut tape to fit more uniformly and tightly around knob, and prevents excessive build-up.



FIGS. 31 and 32.—Showing method of cutting side of tape when applying a large number of either varnished cambria or mica tape to a knob.

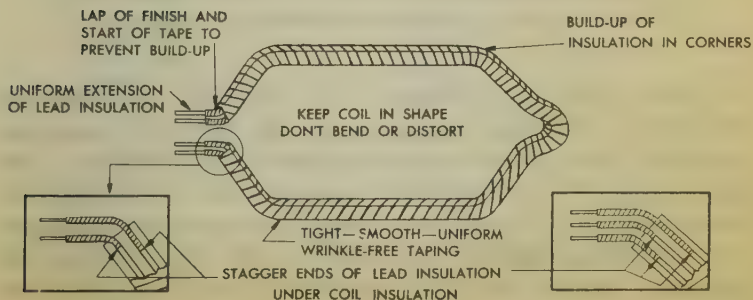
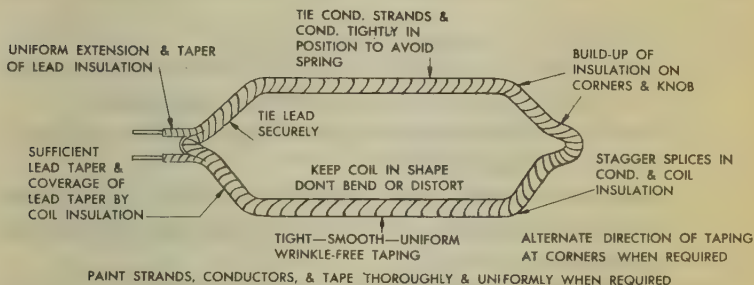
Handling of Coils.—Coils should always be handled carefully since it is easy to damage insulation without leaving visual evidence. A few important points to remember are:

1. Do not hammer or scrape insulation.
2. Do not try to slide tape into position or press out wrinkles or bumps by scraping or pressing with a tool or knife. To correct defects remove and replace tape.
3. Do not lift coils by leads or twist them.
4. Keep coils in shape as much as possible.
5. Keep coils off floors.
6. Do not pile coils on top of each other without supporting each layer.
7. Do not place coils on dirty skids.
8. Do not lean or sit on coils.
9. Do not use unpadded clamps.
10. Do not drop coils on floor, table, or skid. The bump may damage the insulation or get the coil out of shape.
11. Remember that lack of visual physical damage is no guarantee of the absence of serious electrical damage.

Summary.—In summing up, we observe that the characteristics of good stator taping are:

1. Uniform extension of lead insulation.
2. Uniform taper of lead insulation.
3. Sufficient and uniform taper of lead insulation and coverage of lead insulation tape by coil insulation.
4. Lead securely tied in position with coil insulation as well as with the outer finishing layer of tape. It is important to lap finishing layer of tape on lead under that on coil.
5. Conductor strands and conductors tightly tied in position to avoid spring.

6. Strands, conductors and tape thoroughly and uniformly painted with proper varnish, when specified.
7. Insulation at corners at ends of slot portion and at knobs of same uniform thickness as on slot portion and coil ends. Excessive bunching on build-up of insulation at these points should be eliminated.
8. Tight, smooth, uniform, wrinkle-free taping throughout coil and leads.



FIGS. 33 and 34.—Methods of applying insulation to typical coils.

9. Very little, if any, petrolatum or vaseline on tape or coil. This is very important since vaseline reduces the bonding ability of the varnish and produces soft, spongy insulation.
10. Coil shape maintained. Avoid unnecessary bending or twisting of conductors or coils.

Similarly, the characteristics of good armature coil taping are:

1. Uniform extension of lead insulation.
2. Lead insulation applied with one or more turns at start to securely anchor tape and prevent loosening.
3. Lead insulation ends staggered under coil insulation to prevent excessive build-up.
4. Careful starting and finishing of tape to prevent excessive build-up. Trim tape, if necessary to prevent excessive over-lap.
5. Avoidance of over-lapping and excessive build-up of tape at corners and at ends of slot portion.
6. Bonding varnish applied uniformly as required.
7. Tight, smooth, uniform, wrinkle-free taping.

Typical Insulating Methods for Windings of Industrial Machines.—Electrical insulation or the medium separating conductors are defined as non-conductors of electricity. The proper insulation of electrical windings require not only knowledge of materials, but also correct application of these materials. The insulating specifications shown in figs. 35 to 53 are for industrial motors and are supplied by the *Courtesy of the Westinghouse Electric & Manufacturing Co.*

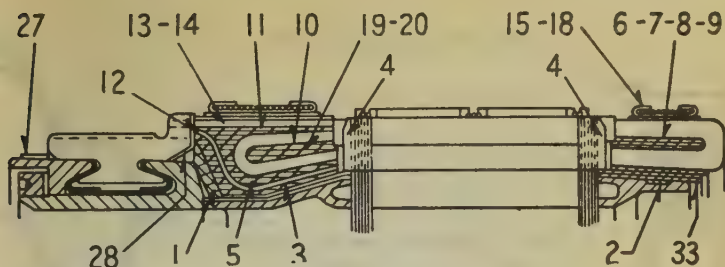
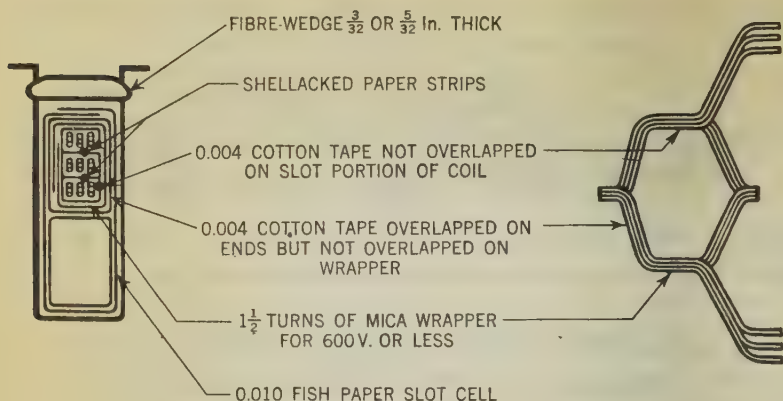
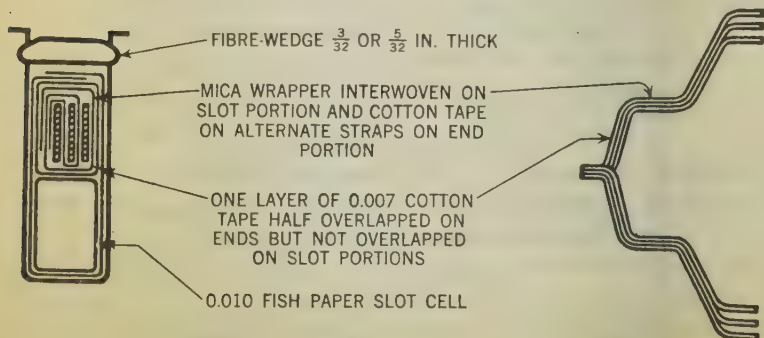


FIG. 35.—Section of typical armature showing different insulating materials used.

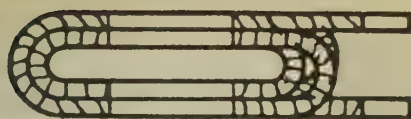
Item	Description of Material	Westinghouse Material Number	Application
1	Moldarta Ring		Back of Commutator
2	Hood (Duck)	1733	Over Rear Coil Support
3	.010"x1" Varnished Cambric Tape	1265	Over Front Coil Support
4	Fishpaper U-piece	1545	Ends of Slot
5	Treated Duck	1232	Between Coil and Bottom Lead
6	Treated Asbestos Strip	1250	Between Rear End Winding
7	Treated Asbestos Strip	1250	Between Rear End Winding
8	Treated Asbestos Strip	1250	Between Rear End Winding
9	Treated Asbestos Strip	1250	Between Rear End Winding
10	Treated Asbestos Strip	1250	Between Front End Winding
11	Treated Duck Strip	1232	Between Coil and Top Leads
12	.023" x 1 1/4" Treated Surgical Tape	7560-3	Through Bottom Leads
13	.023" x 2" Treated Surgical Tape	7560-3	Through Top Leads
14	1" Bias Friction Tape	1821	Around Top Leads
15	Asbestos Strip Cut on Bias	2060	Under Rear End Coil Band
16	.010"x1" Varnished Cambric Tape	1265	Level Under Bands
17	Machine Thread	1828	Assist in Banding
18	Fishpaper and Mica Strip	232	Rear End Coil Band
19	Asbestos Strip Cut on Bias	2060	Under Front End Coil Band
20	Fishpaper and Mica Strip	232	Front End Coil Band
27	Italian Twine	2973	Commutator V-Ring and top lead back of commutator neck.
28	Filling Cement	677	Back of Commutator Neck
29	Shellac	1104	Back of Commutator Neck & V. Ring
30	Shellac	1103	Back of Commutator Neck & V. Ring
31	Black Baking Varnish	2227	Finish
33	Moulded Ring over Coil Support		



FIGS. 36 AND 37.—Showing insulating materials used in direct current armatures with medium size conductors.



FIGS. 38 AND 39.—Showing insulating materials used in direct current armatures with large conductors.



EACH RIBBON TAPED ON
ENDS WITH COTTON TAPE.
ALSO USE TREATED TAPE ON
PHASE COILS.

FIG. 40.—Showing insulating materials used with typical alternating current machine rotor coil.

WEDGE-FIBRE $\frac{3}{32}$ IN. THICK

DOUBLE COTTON COVERED RIBBONS

0.056 IN. THICK FULLERBOARD

0.025 IN. COMBINATION SLOT CELL
EVERY STRAP IS TAPED ON ENDS
WITH COTTON TAPE. ALSO USE
TREATED TAPE ON PHASE COILS



FIG. 41.—Insulating material used in A.C. rotor with medium size conductors.

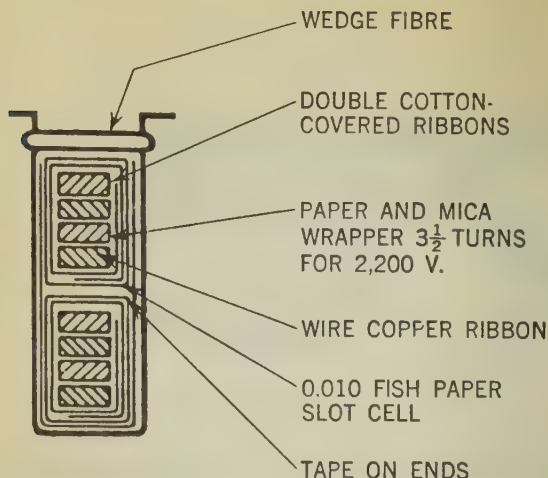


FIG. 42.—Insulating material used in A.C. stators with medium size conductors.

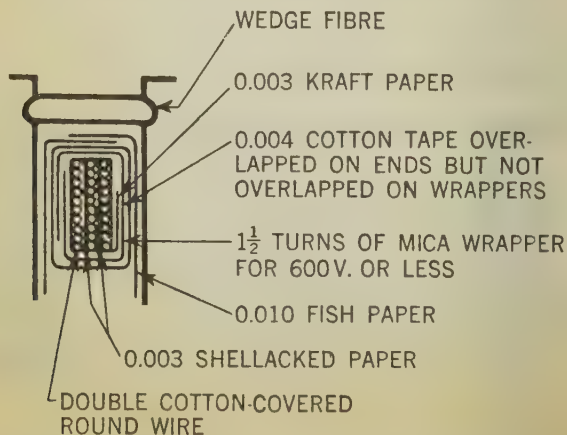


FIG. 43.—Insulating material used in D.C. armatures with small conductors.

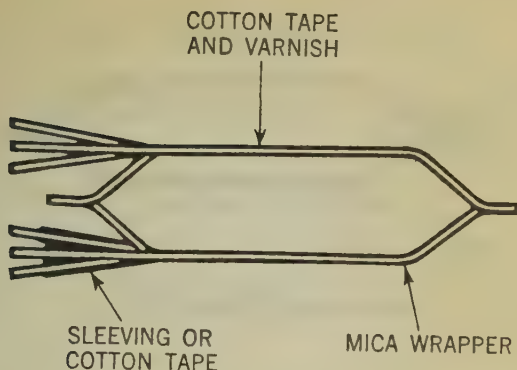


FIG. 44.—Insulating material used in typical D.C. rotor coil.

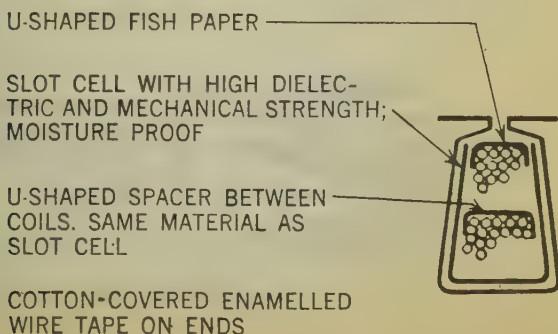


FIG. 45.—Insulating materials used in A.C. stators or rotors with small conductors.

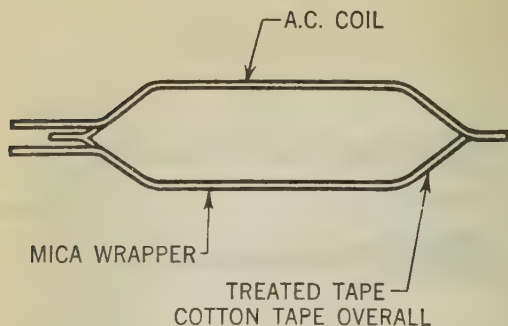


FIG. 46.—Insulating material used in promiscuous wire coil for small A.C. stators.

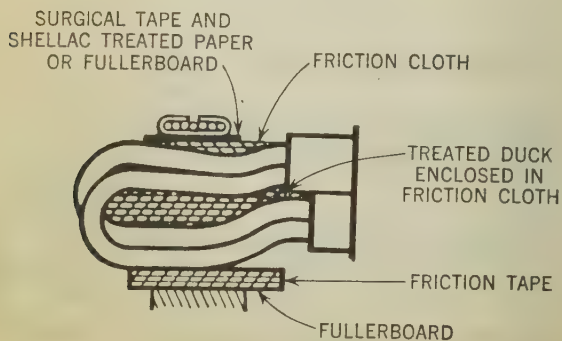


FIG. 47.—Insulating material used in rotor winding.

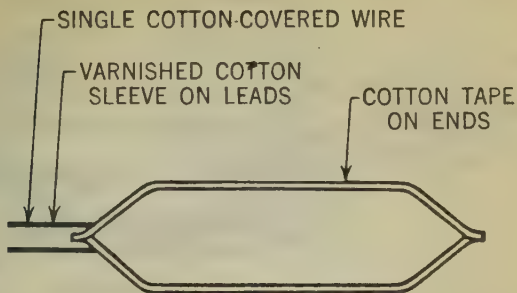


FIG. 48.—Insulating material used in A.C. coil.



FIG. 49.—Showing binding of small rotor conductors.

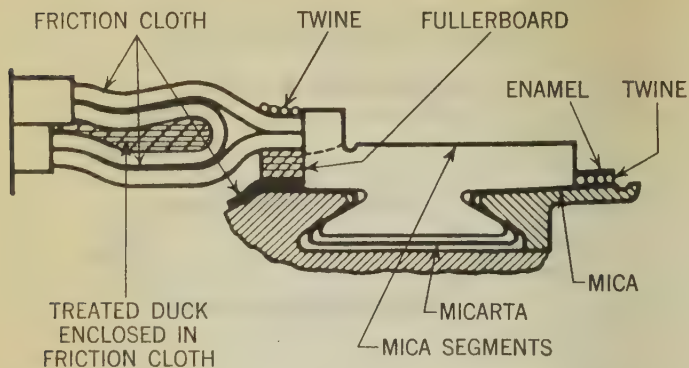


FIG. 50.—Insulating materials used in winding of typical D.C. armature.

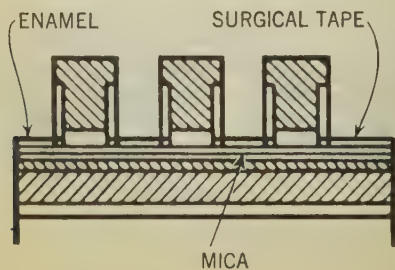


FIG. 51.—Showing slip ring insulation for typical A.C. machine.

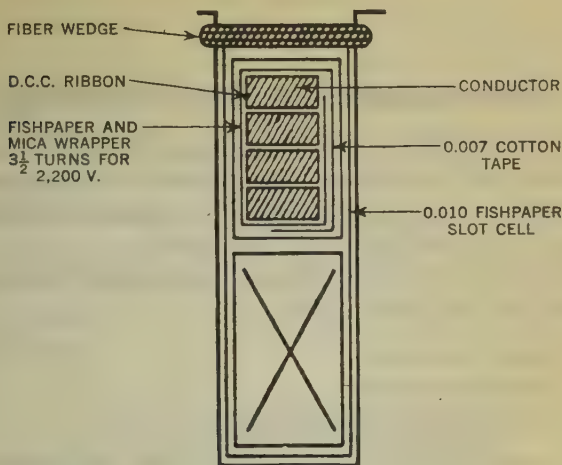


FIG. 52.—Showing A.C. stator with medium size conductors. Class "A" insulation.

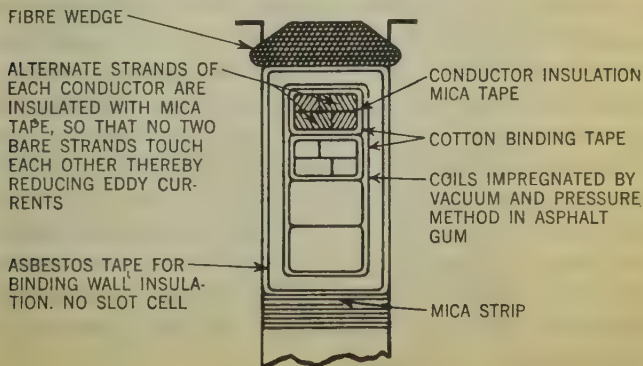


FIG. 53.—Showing cross-section of stator coil, with Class "B" insulation.

Procedure in Coil Winding

Since the insulation and geometrical forms of coils differ, depending upon the size and type of machine to be wound, it is not possible to give anything but a few details of the procedure followed in the production of typical coils.

In making coils in large plants or repair shops there are three principal methods used. They are:

1. Mould winding.
2. Formed winding.
3. Shuttle winding.

The *mould coils* are usually those made on a form rotated on a lathe with all the necessary shaping done in special machines.

By *formed coils* is usually meant those coils made over a stationary form with the bends made by the employment of levers and mallets to form the coil to the required shape.

Shuttle or *pulled coils* are first wound on a simple shuttle such as that shown in fig. 54, which is fastened to a rotating shaft and then placed in an automatic spreading machine and shaped to the proper pitch and radius without the use of tools which in any way could harm individual conductor insulation.

The principal steps in production of a 6,600 volt stator coil is depicted in figs. 54 to 71. The method of insulating coils depends upon the class of insulation, whether Class A, Class B or a modification is required.

The coils previously shown are retained in the stator slots by means of tough fiber leatheroid slot wedges, treated with

varnish to prevent absorption of moisture. The coil insulation is protected in the slot for some distance on each side of the core by slot cells of suitable insulating material. Motors required to withstand severe starting conditions have their coils braced to prevent movement, either by lacing the coil ends to each other, or in higher speed motors, lacing them to special coil support rings.

Stator terminal leads, on smaller motors are usually brought out to sheet metal terminal boxes located on the side of the yoke below the horizontal center line. For larger motors they are usually brought out at the bottom of the yoke without terminal boxes.

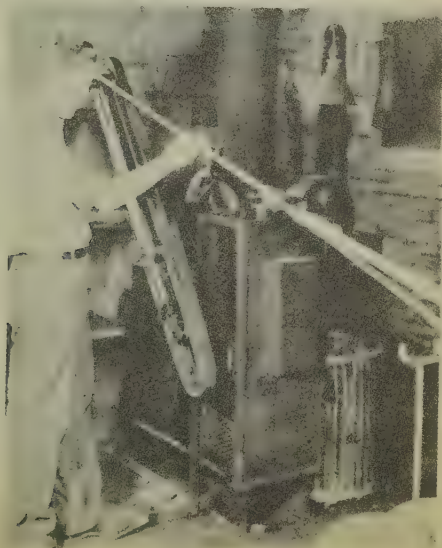


FIG. 54.—Illustrating how the coil is machine wound to its proper dimensions.



FIG. 55.—Coil turns are temporarily held to proper coil shape by steel clips until later bound together by baking varnish and insulation.



FIG. 56.—Illustrating how the coil is formed with mechanical precision by a special machine to fit the stator slots.



Fig. 57.—Showing how a group of coils are immersed in a tank filled with flexible baking varnish.

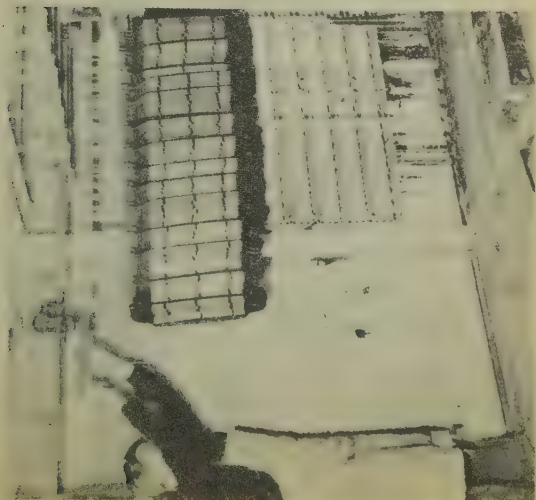


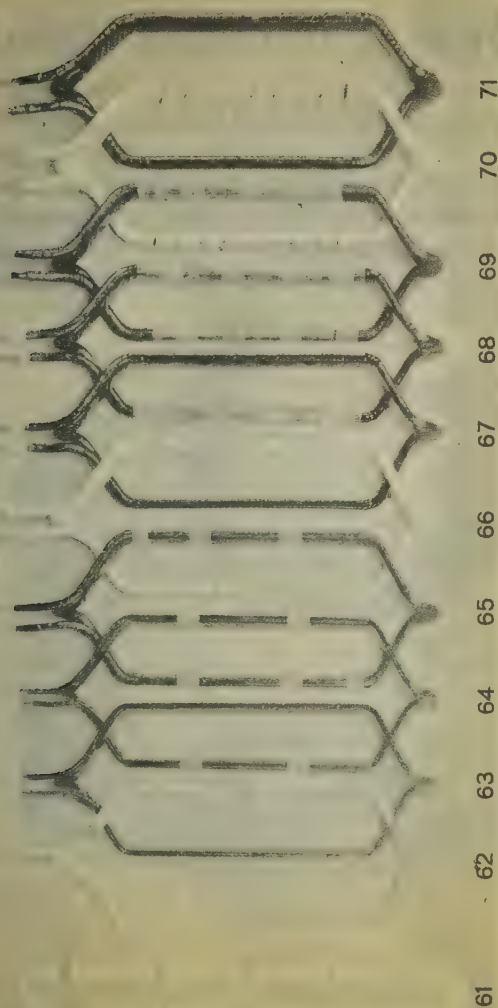
Fig. 58.—After the coils have become saturated with varnish they are baked in an electric oven.



FIG. 60.—This illustration shows how a sheet of flexible mica is tightly wrapped by hand on the straight portion of the coil.



FIG. 59.—In this machine cotton tape is evenly wrapped on the coil.

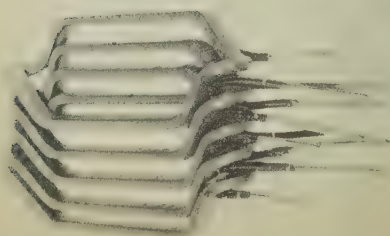
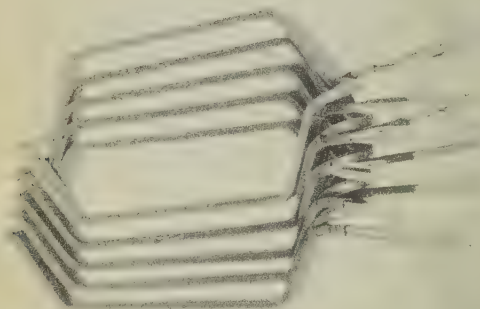


FIGS. 61 TO 71.—Showing the appearance of the coils, figs. 54 to 60, after each process as previously described. Fig. 61 represents the appearance of the coil after it has been wound and metal clips applied. In order that the coils may correctly fit the armature slot after being formed and insulated, it is of the utmost importance that the length of the coil be calculated with the utmost accuracy before the actual work of forming and insulation takes place. Fig. 62, coil formed and oven baked. Fig. 63, coil dipped and baked three times. Fig. 64, six layers of 7-mil black varnished cambric sheet applied with bonding varnish to sides. Fig. 65, eight layers of 7-mil varnished cambric tape, applied to ends. Fig. 66, one layer cotton tape is wound on entire coil. Fig. 67, coil dipped and baked three times. Fig. 68, four layers of 10-mil flexible mica sheet applied to coil sides. Fig. 69, four layers of 7-mil varnished cambric tape applied to ends. Fig. 70, one layer of cotton taped on entire coil. Fig. 71, finally shows the finished coil after the entire coil has been coated with bonding varnish.

Classification of Insulation Materials

The classification of insulation materials according to the *American Standard Association* (ASA) are as follows:

Class "A" Insulation consists of cotton, silk, paper and similar organic material when impregnated or immersed in oil; also enamel as applied to conductors.



FIGS. 72 and 73.—Typical form wound stator coils with *Class "A" insulation*.

Class "B" Insulation consists of mica and asbestos and similar organic materials in built-up form combined with binding substances. If Class "A" material is used in small quantities for structural purposes only, in conjunction with Class "B" insulation, the combined materials may be considered as Class "B," provided the electrical and mechanical properties of the insulated winding are not impaired by the application of the temperature permitted for Class "B" material. (The word "impair" is here used in the sense of causing any change which could disqualify the insulating material for continuous service,)



FIG. 74.—Showing typical stator coil for large machine placed in a special coil cradle to assure correct measurement.

Class "C" Insulation consists of inorganic materials such as pure mica, porcelain, quartz, etc.

Class "O" Insulation consists of cotton, silk, paper and similar organic materials when neither impregnated nor immersed in oil.

Impregnated Cotton, Paper or Silk.—An insulation is considered to be "impregnated" when a suitable substance replaces the air between its fibers, even if this substance does not com-

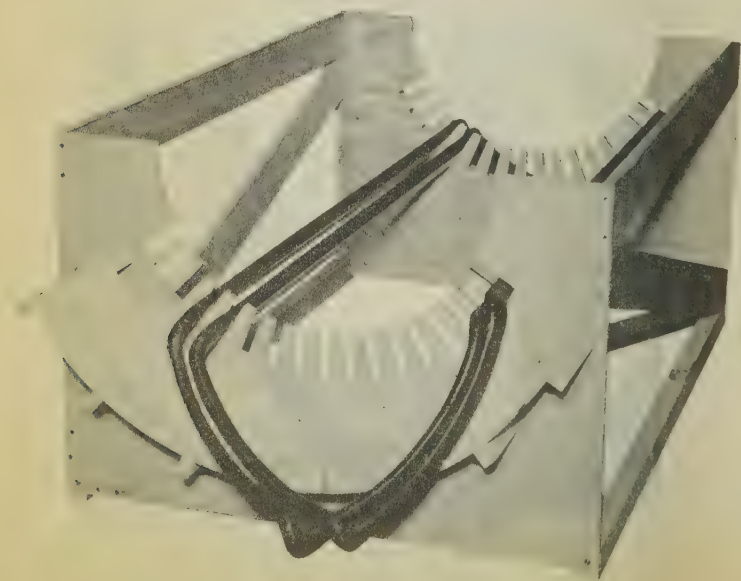


FIG. 75.—Showing reverse side of coil illustrated in fig. 74.



FIG. 76.—Showing portion of a stator with a part of the coils in place. Prior to inserting the coils, the slots in the stator core are lined with a tough fiber paper. The coils which fit snugly in the slots are then put in place. After the coils are inserted, the flaps of the fiber slot liners are lapped over the top of the coils, and the coil wedges are driven in, clamping the coils securely in the slots. The wedge consists here of horn fiber $\frac{5}{16}$ in. thick, are dried and impregnated with paraffin and accurately cut to size in a special milling machine. (Courtesy Electric Machinery Mfg. Co.)

pletely fill the spaces between the insulated conductor. The impregnating substance, in order to be considered suitable, must have good insulating properties; must entirely cover the

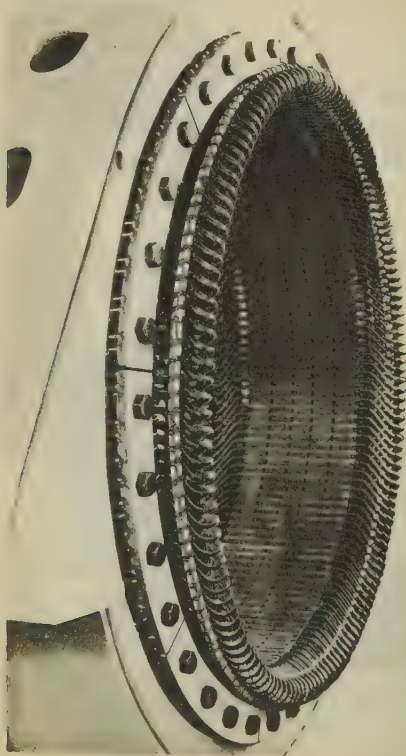


FIG. 77.—Showing one method of supporting stator coils. Here the ends of the coils that project beyond each side of the core are well lashed to minimize coil vibration. The circular bracing ring to which the coil ends are individually lashed are used where the span of the stator coil exceeds approximately 6 in. The bracing ring is strong and well insulated. (Courtesy Electric Machinery Mfg. Co.)

fibers and render them adherent to each other and to the conductor; must not produce interstices within itself as a consequence of evaporation of the solvent or through any other cause; must not flow during the operation of the machine at full working load or at the temperature limit specified; must not unduly deteriorate under prolonged action of heat.

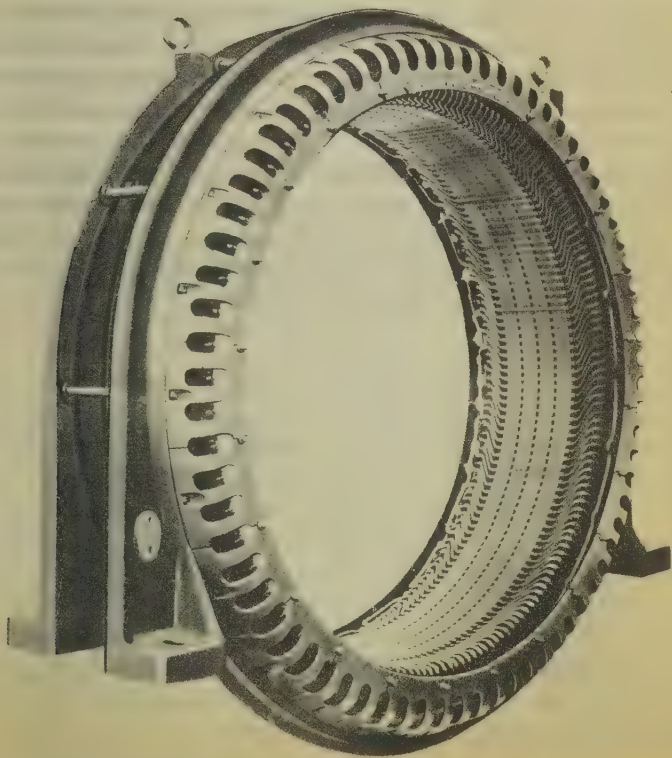


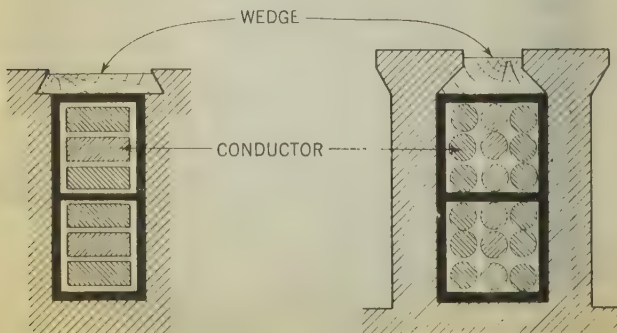
FIG. 78.—Illustrating finished stator for an 845 kva. 257 r.p.m. alternating current machine
(Courtesy Fairbanks Morse & Co.)

Coil Slot Insulation

General.—In A.C. machines, coil slots are generally divided into two classes, namely: The *open* and the *semi-enclosed*.

The open slot, fig. 79, is more commonly used because the coils can be form-wound and insulated prior to the encasement in the slots, thus providing a more economical type of winding.

The semi-enclosed type of slot, fig. 80, is commonly used in wound-rotor induction motors. Because of the necessity to insert the conductors in the slots separately, it is not an economical type of winding and it also requires more coil space. In both types the coils are retained in the stator slots by means of tough fiber or leatheroid slot wedges which are treated with varnish to prevent absorption of moisture.



FIGS. 79 and 80.—Showing an *open* and *semi-enclosed* slot, respectively.

The coil insulation is protected in the slot and for some distance on each side of the core by slot cells of suitable insulating material.

In modern high voltage machines built-up mica is the type of insulation most successfully employed to withstand high temperature and voltage stresses. Another type of insulating material known as fiber-glass with excellent insulating properties is now being used with good results.

In small and medium size motors the slot cells usually consist of fish paper alone or fish paper and treated cloth depending upon the voltage and size of the motor.

Operations Preliminary to Winding.—The following operations should be carefully performed before starting to wind.

1. The coil and insulating materials comprising the windings that go into a slot are usually so proportioned that they completely fill the slots. Hence if any foreign substance were to remain lodged in the slot at the time of winding, it would not leave room for the coil, and an attempt to drive the coil home would probably result disastrously. Therefore, the first step in winding should be a detailed inspection of each slot for foreign substances and irregularities of punchings.
2. Blow all dirt out of the slots with compressed air.
3. Examine the core on both faces for flared out punchings or retaining fingers. If any are found, drive them back until the core is even and straight on both sides.
4. By the location of the terminal block, determine on which side of the core the coil leads should be wound.
5. Mark the slots (top and bottom) indicating the proper throw for the first coil.
6. If the grouping is irregular, mark all the slots into

which the bottoms of the phase coils are to be placed.

7. The windings should always make a tight fit in the slots. In cases where the coil with the customary slot insulation does not make a tight fit, side fillers, bottom fillers or spacing pieces of insulating materials must be used. In order to determine the exact amount of filler needed, try the winding out in one slot. All filler needed in depth should be placed in the bottom of the slot, or between the top and bottom parts of the coils, in order to bring the winding as near to the bore as possible.

From this point on, the procedure will vary, depending on whether the stator has *open slots* or *partially closed slots*.

Slot Insulation.—Several methods of insulating the slots of motors are in use at the present time, the principal ones being:

1. Fish paper cell only.
2. Fish paper and treated cloth cells.
3. Combination cells only.

When a fish paper cell only is used it should be about 15 mils thick and should be cut to extend about $\frac{1}{8}$ in. beyond the fiber punchings.

It should be of such width as to come just to the edge of the tooth tip, that is, it should not obstruct the slot opening passage for wires into the cell. The cell should, of course, be formed to fit the slot if possible. After the slot is wound a $\frac{1}{32}$ or $\frac{1}{16}$ in. thick fiber strip of suitable width should be inserted in the top of the slot under the teeth and between the teeth and the fish paper cell. This fiber wedge should be about $\frac{1}{8}$ in. beyond the punchings.

It should be of such width as to come just to the edge of the tooth tip, that is, it should not obstruct the slot opening passage for wires into the cell. This cell should, of course, be formed to fit the slot if possible. After the slot is wound a $\frac{1}{32}$ or $\frac{1}{16}$ in. thick fiber strip of suitable width should be inserted in the top of the slot under the teeth and between the teeth and the fish paper cell. This fiber wedge should extend about $\frac{1}{8}$ in. beyond the punchings.

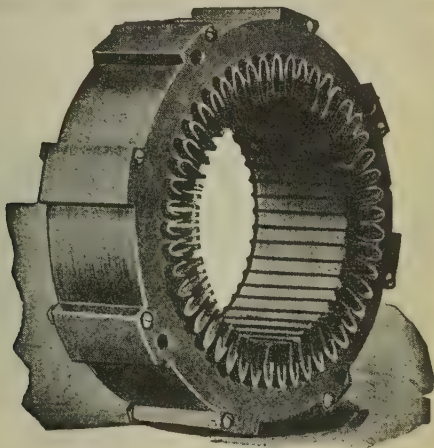


FIG. 81.—Showing a typical polyphase induction motor with slot insulation in place.

The starting winding of split phase motors should be insulated in the slots from the main winding by a fiber strip, as wide as the slot, or by an additional fish paper cell. Where an additional cell is used, the first fish paper cell into which the main winding is wound should be folded over and the second fish paper cell placed on top.

The starting winding should be insulated from the main winding on the ends with drilling or light canvas in case considerable shaping is necessary to form the windings. Where shaping of the end windings is not necessary, no insulation is required between the main and starting windings except that provided on the individual wires and by the insulating varnish which is applied to the completely wound stator.

When a fish paper cell and a treated cloth cell are used, the fish paper cell is usually no more than 10 mils thick and is required merely to prevent the iron puncturing the treated cloth.



FIG. 82.—Showing field core and slot insulation in partially wound induction motor.

This fish paper is the same size and shape as the one described previously. The treated cloth cell extends through the slot opening toward the center about $\frac{3}{4}$ in. to 1 in. After the wires are inserted the treated cloth cell should be cut off flush with the slot and folded over, and the fiber wedge inserted as described.

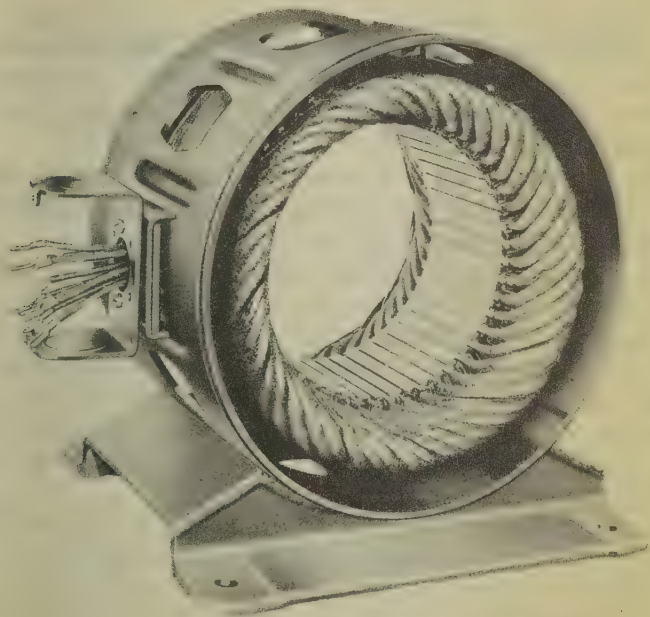


FIG. 83.—Showing completed stator winding. After the windings are in place, the stator is baked to drive out all moisture and while still hot is immersed in heavy insulating varnish. When the heated stator-core is suddenly immersed in the considerably cooler varnish, a suction is created which is largely responsible for the complete impregnation of the winding. The stator is kept immersed sufficiently long for the insulating compound to reach and impregnate the innermost portions of the coils and to completely fill the spaces between wires and slot insulation. The stator is baked until completely dried and is then given additional dipping and baking in order to insure complete impregnation and to provide extra moisture-resisting coat. Finally, the stator is sprayed with an air-drying varnish, which not only provides further resistance to oil and moisture, but also gives the coils a glossy surface for easy cleaning.

The starting winding should be insulated from the main winding where it is wound in the same slot with the main winding the same as described previously, except use a treated cloth cell in addition to the fish paper cell. The starting winding is insulated from the main winding on the ends as described.

When a combination cell is used the procedure is the same as for the fish paper cell.

A combination cell generally consists of a piece of fish paper to which varnished cambric has been attached by means of varnish. The combination cell should be inserted so that the fish paper side is next to the iron.

When necessary, all end windings should be laced and in some cases where the end windings are bulky they should be taped from iron to iron with linen tape.

All small motors should be dipped in varnish and baked, after they are completely wound and insulated.

Any good grade of insulating varnish which does not bake too hard will be satisfactory. Some insulating varnishes require a longer time to bake than others, and some require higher temperatures than others, but in no case should the temperature exceed 125°C . and the length of the baking time should never be less than four hours.

Before immersing the wound primary into the insulating varnish it should be kept heated for several hours at 50°C . to permit it to dry out thoroughly. It should then be immersed immediately into the insulating varnish and allowed to remain there until bubbles cease to rise.

CHAPTER 22

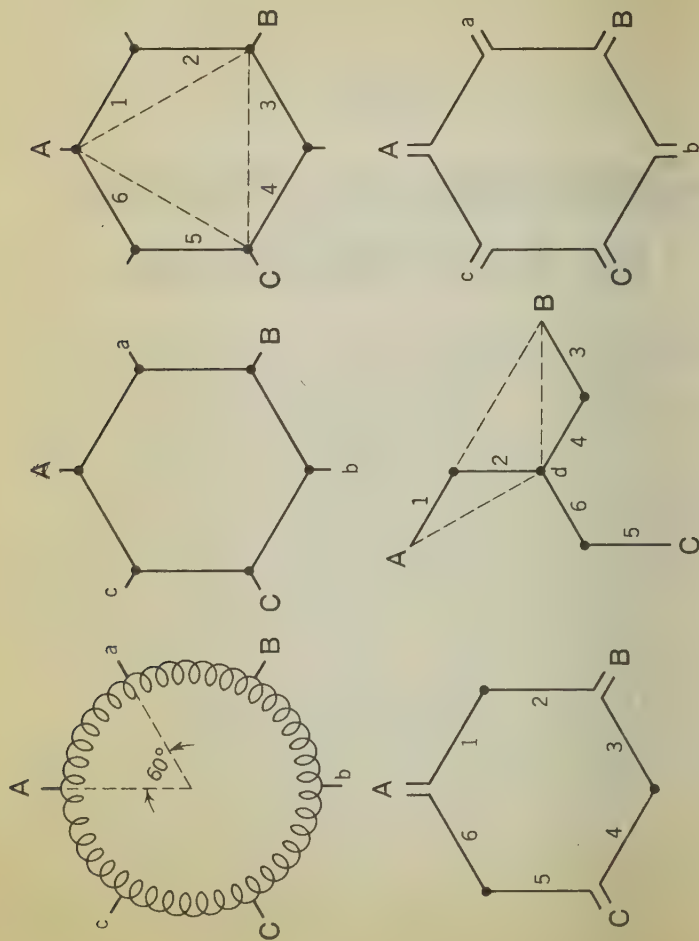
Grouping of Phases In A.C. Windings

Three-Phase Windings.—In the various A.C. windings previously shown, no attention has been paid to the internal connection of the coils to conform with established standards.

All the various types of commercial three-phase windings with their current and voltage relations can be derived in a very simple manner from the consideration of a ring armature with its windings arranged in six symmetrical groups, each covering 60° of the ring, which may all be closed together to form the ordinary closing winding, or which may be separated into either three or six groups and connected to form various *delta* and *star* types of windings.

Let fig. 1 represent such a ring armature closed on itself and with six taps brought out, designated as A, a, B, b, C, c .

By connecting together the points Aa, aB, Bb , etc., as shown in fig. 2, a six-sided figure is obtained, which represents the various voltage and phase relations which can be obtained with all commercial three-phase and six-phase windings. It will be noted that Aa and bC are of equal length and are parallel in direction. The length represents *e.m.f.* and the direction represents phase relation.



FIGS. 1 TO 6.—Showing voltage and phase relations in various polyphase windings.

Therefore, these two groups are of equal *e.m.f.*'s and of the same phase. The same holds true of *aB* and *Cc*, and of *Bb* and *cA*. These groups have also been numbered consecutively from 1 to 6 in fig. 3, so that a given group can be identified by number. This figure is the same as fig. 2 with three leads carried out from *A*, *B* and *C*, to form the three terminals of a three-phase winding.

The dotted lines from *A* to *B*, *B* to *C*, and *C* to *A* represent the voltage and phase relations obtained from this combination. This is a closed coil winding and is the standard arrangement of winding on a three-phase rotary converter.

By opening the closed arrangement of fig. 2 at the points *A*, *B* and *C*, as shown in fig. 4, an open coil arrangement is obtained and the three parts resulting can be recombined in several ways, keeping the same voltage and phase relations of the individual parts.

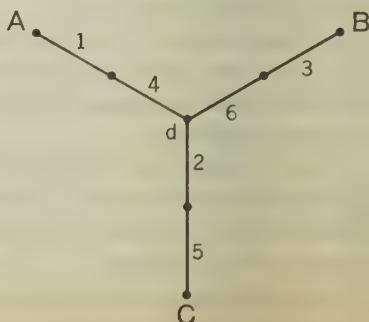
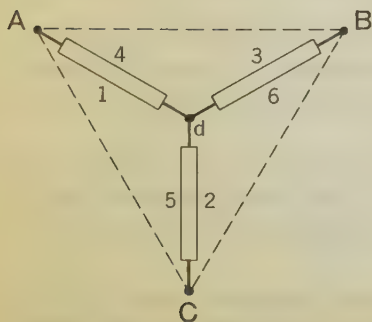
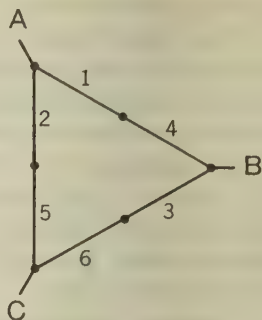
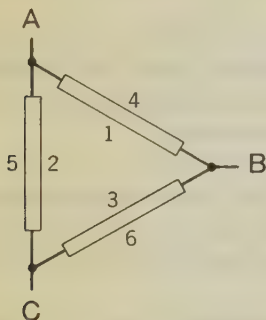
However, only one of these combinations shown in fig. 5 has been used to any extent. This is one form of star winding which is sometimes used to give certain voltage combinations, as will be explained later.

By splitting fig. 2 at six points instead of three, as shown in fig. 6, various other open coil combinations of windings can be obtained while keeping each group or leg in its proper phase and voltage relations.

One of these combinations is shown in fig. 7, in which the groups which are similar in *e.m.f.* and phase are connected in parallel and the three resulting combinations are connected to form a delta winding.

In fig. 8 the two groups of similar phase are shown in series instead of parallel and connected to form a delta. Obviously, figs. 7 and 8 are equivalent, except that the terminal *e.m.f.* of one is double that of the other.

By reconnecting the three components of fig. 7 in the manner shown in fig. 9, a parallel-star winding is obtained. Fig. 10 is equivalent to fig. 9, except that the two *e.m.f.*'s of equal phase are in series instead of in parallel, thus giving just twice the voltage of fig. 9.



FIGS. 7 to 10.—Illustrating various polyphase windings connected to form *delta* or *star* combinations.

Six-Phase Windings.—These have found their use mainly in rotary converters. The foregoing covers all of the usual combinations for three-phase windings, open and closed coil types. The same general scheme may be used to illustrate the six-phase combinations of windings which are frequently used in connection with rotary converters.

In fig. 3, a three-phase winding is shown with terminals at *A*, *B* and *C*. If three other terminals are formed by *a*, *b* and *c*, a second three-phase winding is obtained. The dotted lines in fig. 11 illustrate the voltage and phase relations of these two windings. This is the so-called double delta arrangement, the dotted lines representing the voltage and phase relations of the transformers which supply the rotary converters.

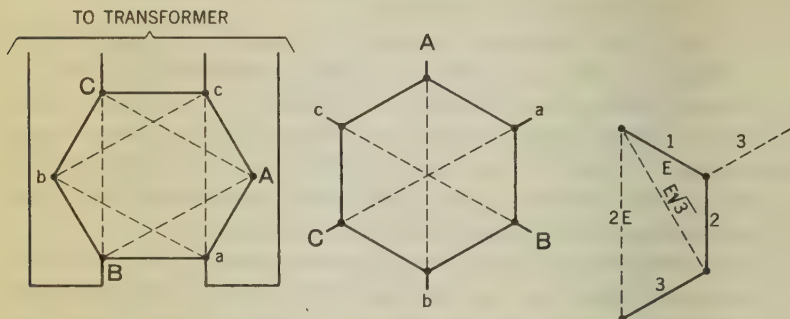
It is evident that the voltage represented by *ac* is equal in value and phase to that represented by *BC*. Therefore, one transformer with two secondaries of equal value could be tapped across these two circuits. Similar statements can be applied to the relations of the other phases in this diagram.

In fig. 2, it is evident that, if six terminals are used, a voltage can be obtained across *Ab*, *aC* and *Bc*. These three voltages are equal in value but have the 60° relation to each other.

Therefore it is evident that these transformers connected to a three-phase circuit can have their secondaries connected to this winding across the indicated points. This arrangement is indicated in fig. 12 and is the so-called diametrical connection of six-phase rotaries. The middle points of the transformer winding from these three circuits can be connected together if desired.

Voltage Relation Obtained from Three- and Six-Phase Combinations.—From an analysis of the geometrical proportions of the foregoing diagrams, the *e.m.f.* relations of the three

combinations can readily be found. It should be pointed out that in the following comparisons, the magnetic field is assumed to be of such distribution that the *e.m.f.* waves will be of sine shape, as this greatly simplifies the various relations.



FIGS. 11 TO 13.—Showing phase combinations used to obtain a double-delta and diametrical type of winding.

Let E represent the effective *e.m.f.* of any one of the six groups in fig. 2. Then combining the various groups geometrically, taking into account the angular relations, the various *e.m.f.*'s can readily be derived. They are as follows:

In fig. 3, the *e.m.f.* across AB , BC , etc. $= \sqrt{3}E = 1.732E$. In fig. 5, the *e.m.f.* Ad is the same as AB in fig. 3 and is, therefore, equal to $\sqrt{3} \times E$, but the *e.m.f.* AB in fig. 5 is equal to $\sqrt{3} \times Ad$. Therefore, the *e.m.f.* of $AB = \sqrt{3} \times \sqrt{3} \times E = 3E$.

In fig. 7, AB is evidently equal to one group or side of fig. 2, and the *e.m.f.* of $AB = E$. In the same way the *e.m.f.* of fig. 8 $= 2E$. In fig. 9, the *e.m.f.* Ad is evidently equal to E , and the *e.m.f.* $AB = \sqrt{3} \times \text{e.m.f. of } Ad$. Therefore, the *e.m.f.* of $AB = \sqrt{3} \times E = 1.732 E$, or

same as fig. 3. In the same way the *e.m.f.* of *AB* in fig. 10 = $2\sqrt{3}E = 3.464 E$.

For the six-phase combinations the following *e.m.f.*'s are obtained: In fig. 11, each of the deltas is the same as in fig. 3, and the *e.m.f.*'s are the same and are equal to $1.732 E$. In fig. 12, *Ab* is geometrically equal to twice *aB* and the *e.m.f.* *Ab* is equal to $2E$.

When considering only three-phase, delta or star-voltage or currents, the following simple relations will be obtained with reference to fig. 9, we have:

Delta-voltage = 1.732 times *star-voltage*. Thus the delta-voltage is the higher one, the star-voltage being only a part of the delta-voltage.

Similarly a distinction is made between the *delta-current* and the *star-current* in a three-phase system. The *delta-current* is the current which flows from phase to phase, that is, from *A* to *B*, from *B* to *C*, from *C* to *A*.

The *star-current* is often simply denoted as the current, current per phase, etc. Line current is the current flowing in the phase conductors in *A* or *B* or *C*, and may be supposed to flow towards the neutral *d*. We obtain:

Star-current = 1.732 times *delta-current*. When speaking of the voltage and the current or line-voltage and line current of a three-phase system without further qualifications, the *delta-voltage* and the *star-current* are understood.

In the conventional denotations, voltage and current in a three-phase system thus, do not correspond to each other, and are not in phase with each other on a non-inductive load, but show a phase displacement of 30° , the angle *dAB*, fig. 9.

Voltage Relation Obtained from Two-Phase Windings.—The voltage obtained in two-phase windings may be calculated in a manner similar to that of three- and six-phase combinations. Assuming a ring, as in fig. 14, with four taps brought out 90° apart and assuming that this winding is the same as that in fig. 1, then the following *e.m.f.*'s are obtained:

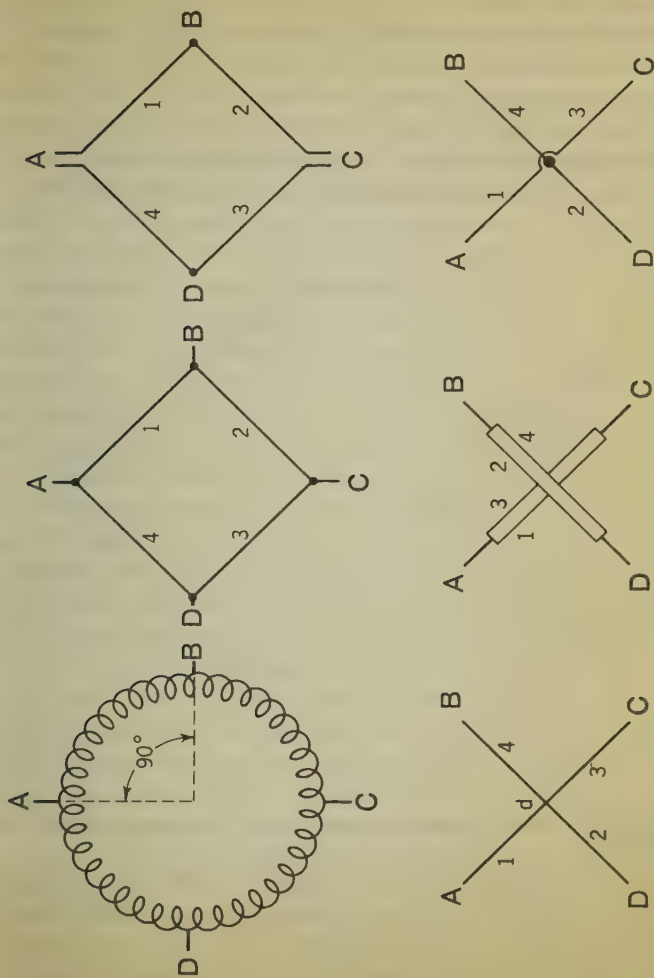
Fig. 15 represents a closed coil two-phase winding corresponding to the three-phase winding in fig. 3. Calling E_1 the *e.m.f.* of each group, the *e.m.f.*'s AC and $BD = \sqrt{2} \times E_1$. By opening fig. 15 at two opposite points, as in fig. 16, the two parts may be rearranged to give fig. 17.

This is an interconnected open coil two-phase winding; that is, the central points are connected together so that there are fixed *e.m.f.* relations between all four terminals. The *e.m.f.* Ad is equal to E_1 , and the *e.m.f.* across AB , BC , etc. $= \sqrt{2} E_1$, while the *e.m.f.* across AC and $BD = 2 E_1$.

By splitting the winding in fig. 16 at four points, the arrangement shown in figs. 18 and 19 are obtained. These two windings are equivalent, except that in fig. 18, the two groups which are in phase are connected in parallel, while in fig. 19 they are series.

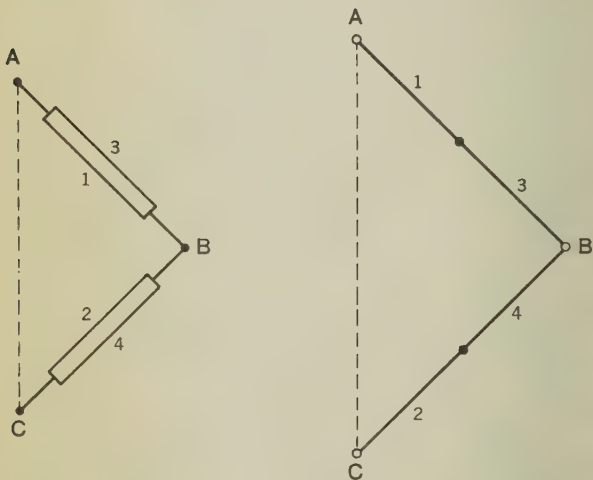
If the middle points in fig. 19 are connected together the arrangement becomes equivalent to fig. 17. In fig. 18, *e.m.f.*'s AC and BD are equal to E_1 , while there is no fixed *e.m.f.* relation between AB , BC , etc. In fig. 19, the *e.m.f.*'s AC and BD are equal to $2E_1$, and there is no fixed relation between AB , BC , etc.

In figs. 20 and 21 the usual two-phase three-wire arrangement is shown. In fig. 20 $AB = E_1$ and $AC = \sqrt{2} \times E_1$. In fig. 21, $AB = 2E_1$, and $AC = 2 \times \sqrt{2} E_1$.



FIGS. 14 TO 19.—Showing voltage and phase relations obtained in two-phase windings.

Closed Coil Types.—The closed coil type of winding is always used with rotary converters. The controlling feature in this case is that the rotary converter carries a commutator, which naturally requires a closed coil type of winding. Rotary converters are, in practice, wound for three-phase, four-phase (usually known as two- or quarter-phase) and six-phase; and the number of collector rings is 3, 4 and 6, respectively.



FIGS 20 and 21.—Showing voltage and phase relations in a two-phase three-wire winding arrangement.

The three-phase winding is generally used in small capacity converters. While the three-phase winding allows less output than the four-phase or six-phase, on small converters the capacity is usually not limited by the armature copper loss, while the use of three rings somewhat simplifies the machines.

Four-phase converters are used to a very considerable extent in connection with two-phase circuits. However, where the supply circuit is three-phase, it is rare that the transformation is from three-phase on the supply circuit to the two-phase on the converter, as there are certain disadvantages in such transformation which more than offset the slight advantage of the four-phase converter over the three-phase.

Moreover, where a higher number of phases is of advantage in a rotary converter, it is practicable to transform from the three-phase supply circuit to six-phase for the converter. Two arrangements of such six-phase transformation are in use, as illustrated in figs. 11 and 12. One of these is the so-called "Double Delta" arrangement, in which each of the step-down transformer circuits is equipped with two secondaries, as indicated in fig. 11. These are connected to form two separate deltas, one being inverted with respect to the other.

The other arrangement is the so-called "diametrical" arrangement, as shown in fig. 12. This has advantage over the the double delta in that only one secondary circuit is required for each phase and the middle points of these secondary circuits may be connected together for a neutral or middle wire between the direct-current leads from the rotary converter.

In a rotary converter the armature copper loss is generally so small, compared with that of the straight direct-current or straight alternating-current machine with the same winding, that all considerations of the comparative heating of three-phase, four-phase and six-phase windings, as on alternating current generators, has practically no bearing on the rotary converter rating.

In a rotary converter, an increase in the number of phases over six represents a considerable reduction in the armature copper loss—much more so than in the closed coil alternating-

current generator. This is due, in the rotary converter, to the fact that one armature winding carries both the direct and the alternating currents, which are to a certain extent flowing oppositely.

Closed coil windings are also occasionally used on the secondaries of induction motors in order to give a better choice in the number of slots than would be allowed otherwise. Such windings when used on induction motors are usually of the two-circuit or series type for the purpose of increasing the voltage as much as possible and at the same time keeping the number of conductors small, while retaining the closed coil arrangement.

A two-circuit closed coil winding will close upon itself symmetrically if the number of turns or coils is one more or less than a multiple of the number of pairs of poles. This sometimes allows the use in the secondary of an induction motor of a number of coils or slots which has no close numerical relation to the number of primary slots. For instance, if the primary of a four-pole induction motor has 48 slots with an open coil, star or delta winding, then with 39 coils and slots in the secondary, a symmetrical closed coil three-phase winding could be obtained, while if an open coil secondary were used, the number of slots should preferably be 36 or 42, which might not be as desirable as 39 in some cases.

This simply illustrates an occasional use of the closed coil winding. Such windings were at one time used very extensively on low voltage, rotating armature, two-phase generators. Such generators were very satisfactory for delivering a relatively large percentage of their rating single-phase.

Furthermore, with one conductor per slot and with bolted-on end connectors, the potential between adjacent end connectors was at all points relatively low. The symmetrical arrangement of such windings also rendered them very suitable for

use with supporting bands or end bells over the end winding. However, with the advent of the rotating field machines, and particularly with the use of higher voltages, the open coil star winding has entirely superseded the closed coil type of generator winding.

Three-Phase Star Windings.—Two types of star windings have been shown, namely, those in figs. 5 and 10. That of fig. 5 gives less output than that of fig. 10 in the ratio of 86.6:100. There would appear, therefore, to be no use for the fig. 5 arrangement; but, in certain cases, in using a given winding it may be desired to reduce the voltage from 12 to 15% while retaining normal conditions otherwise. In such a case the lower voltage could be obtained, if a new winding were used, by simply chording the winding one-third the pitch. On the other hand, if an existing winding is to be used, the same result could be obtained by coupling, as in fig. 5.

In induction motors the arrangement shown in fig. 5 may be used occasionally where the windings are arranged for coupling for two different speeds. In some cases this type of winding may give better average field distribution for the two numbers of poles than the one shown in fig. 10. In this case it is the distribution of the magnetic field, and not the capacity of the winding, which is the important feature.

The arrangement shown in fig. 10 is the true star winding which is used almost universally on three-phase machines. For a given voltage it requires fewer conductors than any other type of winding. This is of very material advantage in allowing a smaller number of conductors per slot, with a given number of slots, which as a rule, allows a better utilization of the slot space, that is, more copper can be gotten into a given slot.

In relatively high voltage machines, where the conductors may be very large in number and small in size, the star winding with its smaller number of conductors, each of much larger size, gives more substantial coils than any other arrangement. Another advantage of the three-phase winding is its fairly good utilization of copper when operated on single-phase.

When operated on purely single-phase load, one group of the star could, of course, be omitted, but if it is retained it becomes a reserve winding which may be used in case of an accident to one of the active groups of the winding. By opening any defective coil in an active group and connecting in the reserve group in place of the defective one, the machine can still develop its specified rating on single-phase.

Still another advantage of the star type of winding is the readiness with which the central or neutral point can be grounded, which is a very considerable advantage in some high voltage systems.

Delta Type Winding.—The true delta type winding, as illustrated in figs. 7 and 8, is not used to any great extent in either alternating-current generators or induction motors. For a given voltage it requires 73% more conductors, each of 58% of the capacity of those of the true star type of winding.

As the terminals of all three groups are connected in a closed circuit, it is necessary that the *e.m.f.*'s generated in the three should balance each other at all instants or there is liable to be circulating current around the windings. This means that the winding must be applied only where the conditions are favorable, or the conditions in the design must be made to suit the type of winding.

This type of winding is occasionally used on low voltage turbo-generators of fairly large capacity, due to the fact that the delta type winding requires more conductors than the star type.

CHAPTER 23

Winding Connections for Polyphase Machines

General.—The design of a motor or generator winding depends for the most part upon its application, the size and speed of the machine, the voltage frequency and the number of phases of the circuit on which it is to be operated.

Consideration of designs and commercial manufacture also determine the number of slots and size and number of coils for a given machine. Having determined these features, the problem of connecting the coils into the proper number of series or parallel circuits remains.

Group Windings.—These may be defined as that class wherein the total winding is divided into separate parts, composed of adjacent coils or conductors. The grouping is an arbitrary one in the case of *lap* and *wave* windings, the coils being all similar and divided into groups solely by their connections.

The number of coils per group may equal the number per pair of poles, divided by the number of phases, or the number per pole divided by the number of phases, the latter method of grouping being so generally used on modern machines that it will be assumed throughout the present chapter, unless otherwise noted.

Thus, in fig. 1, a six-pole, three-phase winding of 36 slots, the number of coils per group $= 36/6 \times 3 = 2$. Where the number of slots is not evenly divisible by the product of poles and phases, dissimilar groups must be employed. In such cases it is advisable to arrange the grouping so that all the phases have an equal number of coils and if possible the grouping should be arranged symmetrically with respect to the core itself, as in fig. 2.

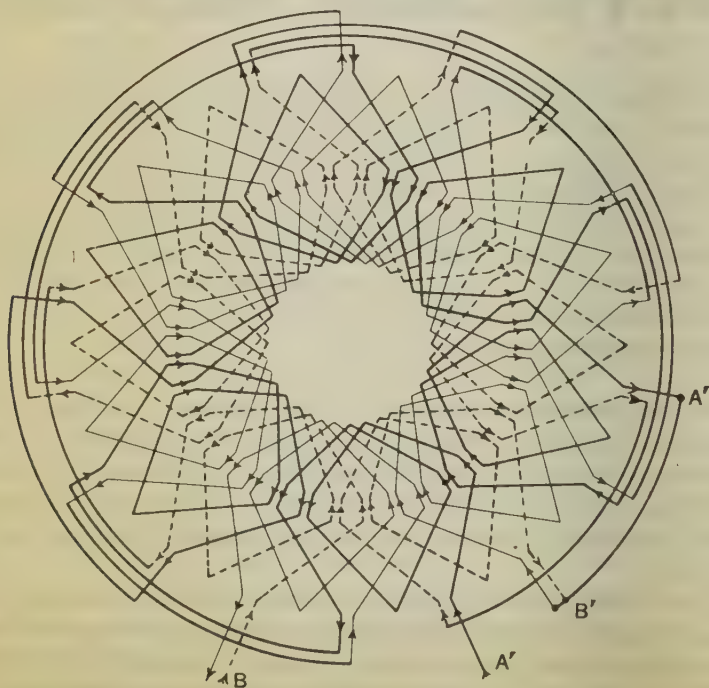


FIG. 1.—Group winding, full pitch, three-phase, six poles, 36 slots, 36 coils, two coils per slot, two coils per group, throw 1-7. Connected in *series star*.

To prevent local currents, which may prove injurious, all circuits which are in parallel must have an equal number of coils and should be symmetrically arranged with respect to each other and to the other phases.

Although only one turn coils are shown in the accompanying diagrams, the same connections are applicable to windings having any number of conductors per coil. These conductors

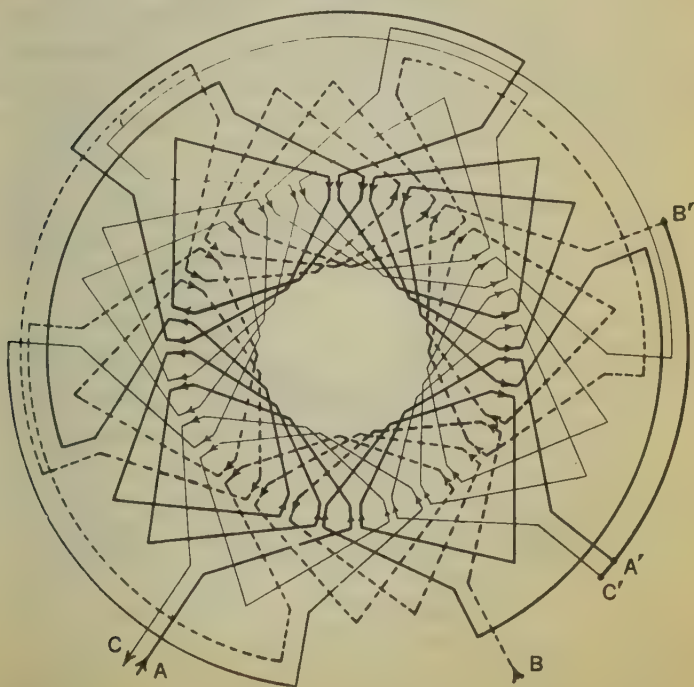


FIG. 2.—Group winding, unequal groups, three-phase, four poles, 30 slots, 30 coils, two coils per slot, two and three coils per group, throw 1-8. Connected in *series star*.

may all be in series, in which case there is one lead at each end of the coil, or the conductors may be divided into any number of equal parallels, in which case there are as many leads at the ends of the coil as there are parallel circuits.

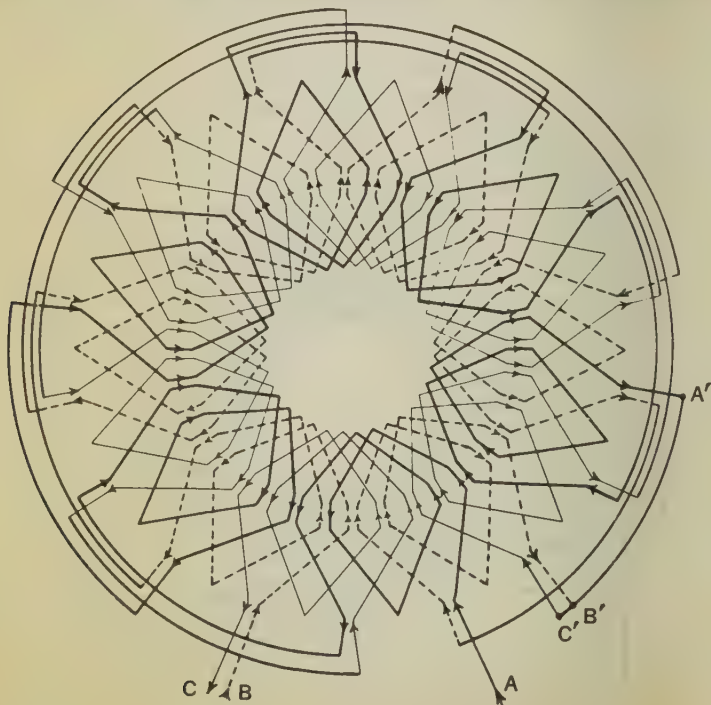


FIG. 3.—Group winding, fractional pitch, three-phase, six poles, 36 slots, 36 coils, two coils per slot, two coils per group. Throw for full pitch 1-7, throw as wound 4-6. Connected in series star.

The leads at the beginning and end of the coil are connected in the same manner as indicated for the one turn per coil winding. For the sake of simplicity, the number of coils per group, hence the total number of coils in the diagrams, has been kept lower than is generally found in commercial machines.

Full and Fractional Pitch Windings.—The number of slots in the core, divided by the number of poles gives a value of the pole arc expressed in terms of the slots. A full pitch winding is one in which the effective span of the coils is equal to the pole arc, and a fractional pitch winding is one in which the effective span of the coils is not equal to the pole arc, as shown in fig. 3.

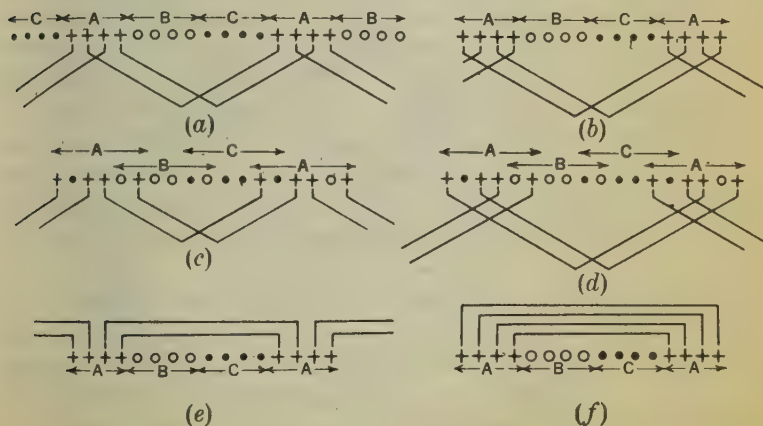


FIG. 4.—Selection of pitch for one coil per slot windings. *a*, full pitch, effective span 12, actual span 11, throw 1-12; *b*, full pitch, effective span 12, actual span 13, throw 1-14; *c*, fractional pitch, effective span 10, actual span 9, throw 1-10; *d*, fractional pitch, effective span 10, actual span 15, throw 1-16; *e*, concentric group, full pitch, effective span 12, actual span 9, 11, 13 and 15, throw 1-13; *f*, concentric group, full pitch, consequent poles, effective span 12, actual span 9, 11, 13 and 15, throw 1-13.

For a two coil per slot, lap or wave winding, the effective span of the coil is equal to the actual span of the coil. In this case the full pitch winding is one where the coil lies in slots 1 and

$$\left(\frac{\text{total number of slots}}{\text{number of poles}} \text{ plus } 1 \right).$$

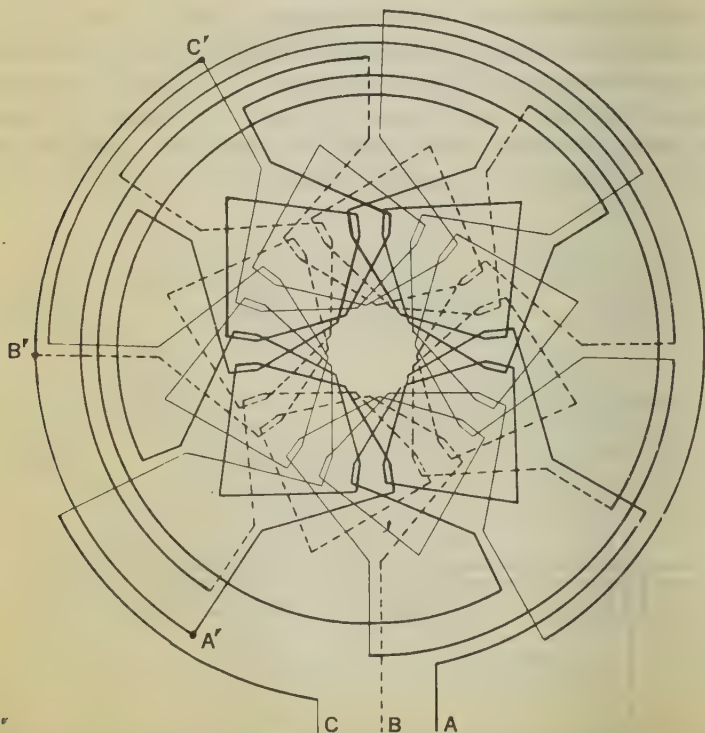


FIG. 5.—Group winding, full pitch, three-phase, four poles, 24 slots, 24 coils, two coils per slot, two coils per group, throw 1-7. Connected in *series star*. Connected for alternate voltages so that when connected in parallel, the groups in each parallel circuit will be distributed around the core.

For a one coil per slot lap winding the effective span of the coil may be greater or less than its actual span. Fig. 4, *a* and *b*, show two different coils in each of which the effective span is the full pitch of 12 slots while the actual span in *a* is only 11 slots and that in *b* is 13 slots. Needless to say, *a* is more generally used on account of the saving in copper and space for end connections. A coil with a span either less or greater than that shown would result in a fractional pitch, as in *c* and *d*.

Representative cases of concentric group windings are shown in fig. 4, *e* and *f*, *e* representing a three-bank winding, in which the number of coils per group equals the total number of coils per phase divided by the number of poles, while *f* represents a two-bank winding of the consequent pole type in which the number of coils per group equal the total number of coils per phase divided by the number of pairs of poles. Neither of these types can be conveniently wound with a fractional pitch, especially with formed coils.

Where dissimilar groups are employed, that is, where the number of slots is not evenly divisible by the product of phases and poles, the full pitch is frequently not a unit and hence a fractional pitch is necessary. Thus in fig. 2 full pitch covers a span of 7.5 slots and the nearest lower even pitch gives a throw of 1-8.

In general, fractional pitch affects the performance of the apparatus similarly to a reduced number of turns in the winding, but not in the same proportion. In a generator this reduces the voltage of the machine.

In an induction motor the maximum available torque is increased, but the densities in the magnetic circuit are also increased with a resulting reduction of power-factor. For either motor or generator, considerable copper may thus be saved in the coil ends and a standard frame may frequently be used for special purposes.

The Simplified Diagram.—By referring to figs. 1 to 8, it is evident that for all combinations the number of diagrams necessary would be unlimited. A simplified diagram may be employed which will not only reduce the required number of such diagrams, but will also minimize the labor in tracing out the connections. Thus it will be seen that the diagram in fig. 9 will satisfy all requirements for connections of groups for the diagrams in figs. 5 and 6.

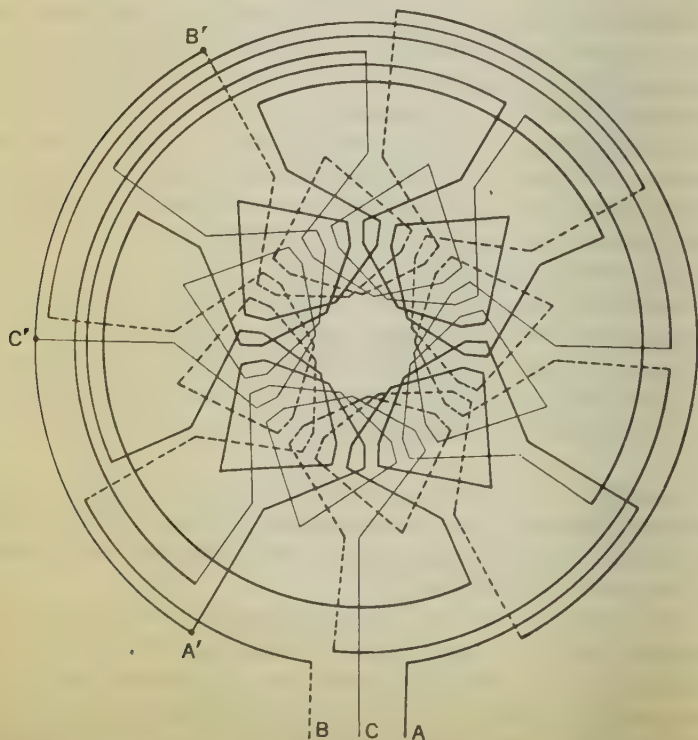


FIG. 6.—Group winding, full pitch, three-phase, four poles, 48 slots, 24 coils, one coil per slot, two coils per group, throw 1-12. Connected same as fig. 5.

It will also apply for any similarly connected three-phase, four-pole, *series star* lap-winding, irrespective of the number of coils per group (provided the groups are regular) or of the throw of the coils, that is, whether the winding is full or fractional pitch.

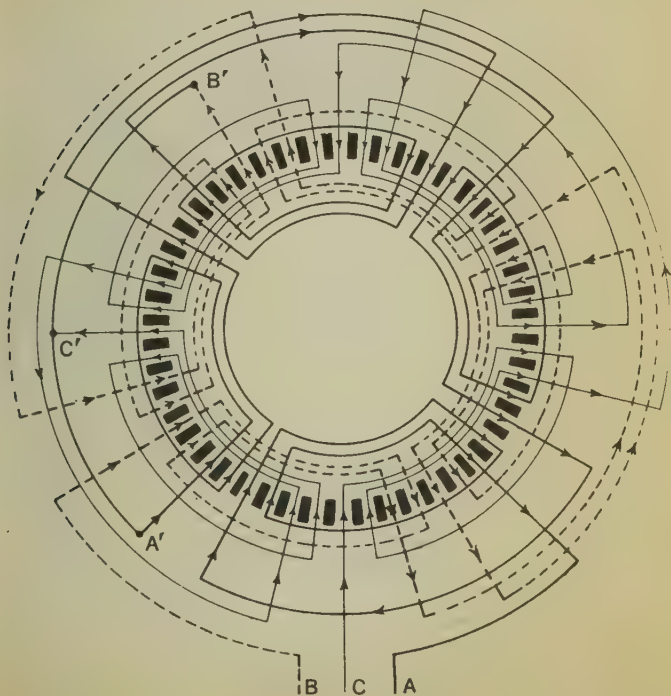


FIG. 7.—Concentric group winding, full pitch, three-phase, four poles, 48 slots, 24 coils, one coil per slot, two coils per group, throw 1-11. Connected in *series star*.

This information for the throw of the coil and the number of coils per group may be carried on the same specification with the remaining winding constants. The groups are formed by

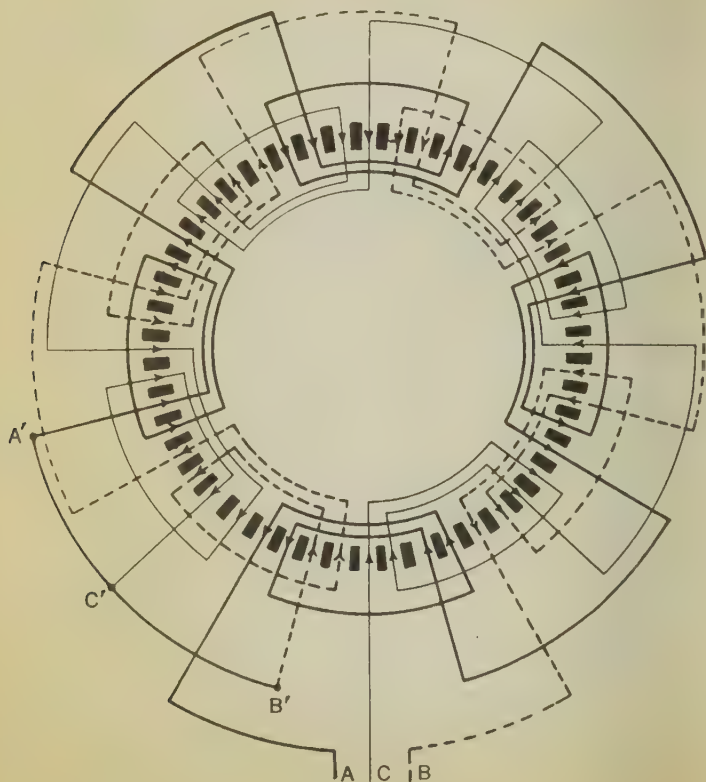


FIG. 8.—Concentric group winding, consequent pole type, full pitch, three-phase, eight poles, 48 slots, 24 coils, one coil per slot, two coils per group, throw 1-7. Connected in *series star*.

connecting the required number of coils together, the end of the first coil to the beginning of the second, etc., the beginning of the first coil and the end of the last coil in the group forming the beginning and end of the group.

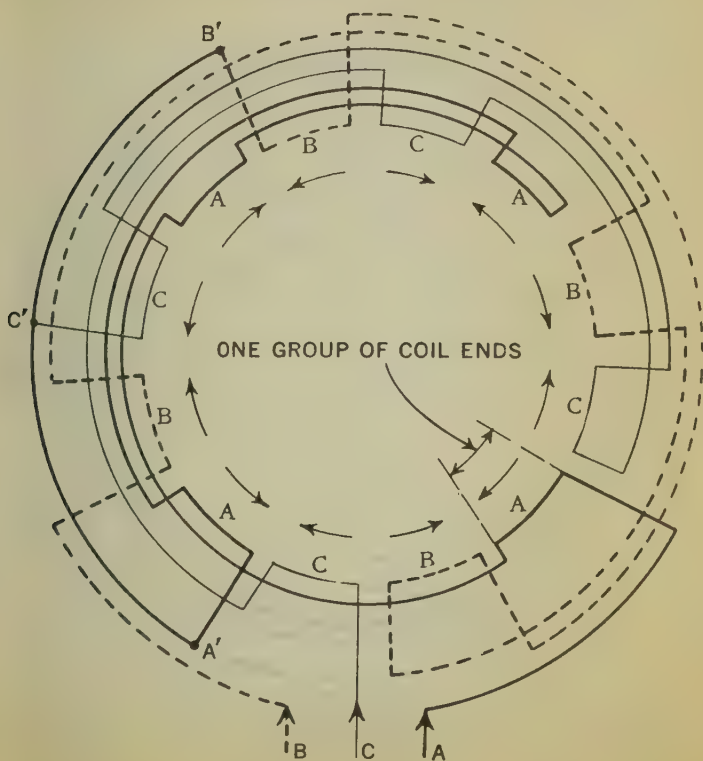


FIG. 9.—Simplified diagram, three-phase, four poles. Groups connected in *series star*. This is a general diagram, of which figs. 5 and 6 are particular examples, and is applicable for any number of coils per group, and any pitch of coils.

Such diagrams may be made for any number of phases, poles or possible parallel circuits, and for any desired method of connection of the groups. In case the coils per group are irregular or unbalanced, it is advisable to have a special diagram giving the number of coils in each group, their location and any other information necessary.

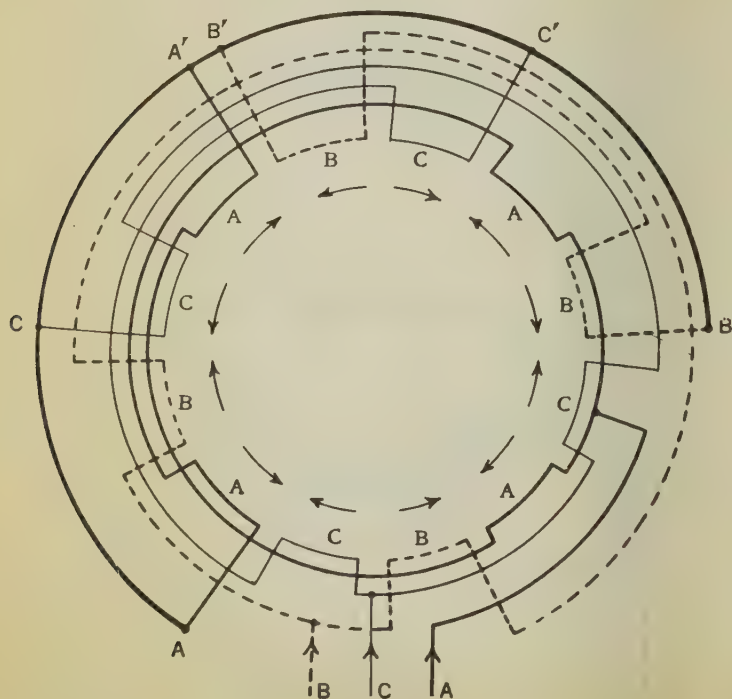


FIG. 10.—Simplified diagram, three-phase, four poles. Groups connected in two *parallel star*. This is the same winding as shown in fig. 9. Connected in *parallel*.

It is obvious that if a winding gives satisfactory operation on a certain voltage, a similar winding of one-half the number of series conductors, but of double the current carrying capacity, will give satisfactory operation on one-half the voltage.

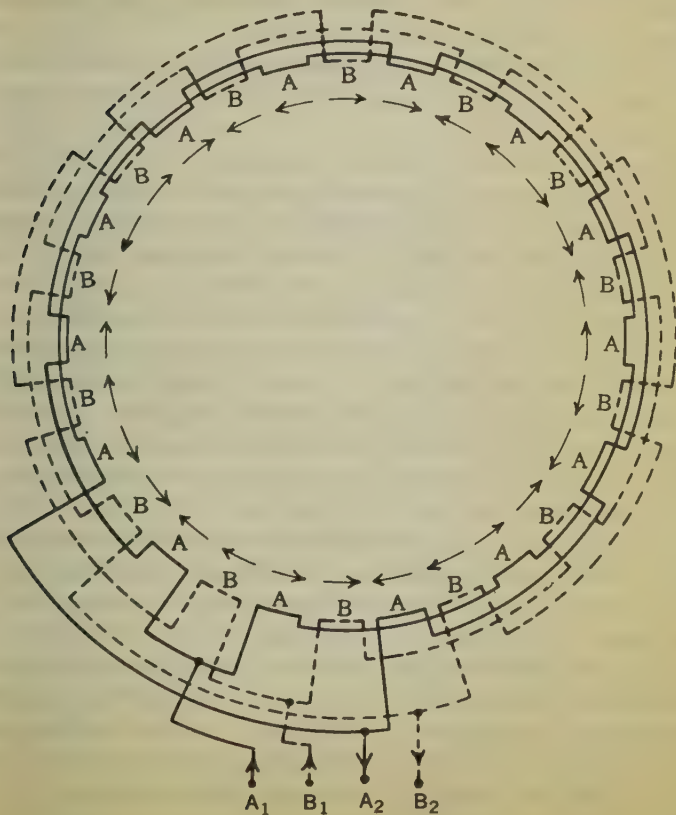


FIG. 11.—Simplified diagram, two-phase, 14 poles. Groups connected in two parallels.

This latter condition may be obtained by paralleling the groups, as in figs. 10 and 11, or where this is impossible by paralleling the series conductors in the slots. For example, if the full voltage connection of a 14-pole motor corresponds to the parallel connection, the only method to change to half voltage would be to change the winding itself, since 14 poles do not permit of a four-parallel connection.

Again an irregularity of coils per group will at times prevent doubling the parallel circuits where otherwise this might be possible.

When it is desired to use one winding for either full or half voltage, the winding, if possible, is laid out for equally satisfactory operation on either connection, and for the minimum amount of labor required to connect from one to the other. This is exemplified by figs. 5, 6, 9 and 10.

It is evident that any eccentricity of the rotor with respect to the stator will affect equally the circuits which are in parallel. In contrast to this are figs. 1, 2 and 3, which if connected in parallel, would place the parallel circuits on opposite sides of the machine and any eccentricity of the two elements will mean an unbalancing of the current in the two halves of the winding.

A simple method for obtaining the proper polarity of the groups is indicated in figs. 9 and 10 for three-phase winding, and fig. 11 for two-phase winding. In a three-phase star winding by traveling from each of the three leads to the star points, the direction of travel is reversed in adjacent groups.

In a two-phase diagram the only necessary precaution in determining the proper polarity is to remember that adjacent groups of the same phase are reversed. By marking the groups *A*, *B*, *C*, etc., and indicating the direction of travel, it is a simple matter to connect them in the proper direction.

Additional index marks may be given on the diagram to aid in connecting the winding, by marking those group ends which are joined by the same connector, with the same numeral.

Any star diagram can be changed readily into a corresponding delta diagram by opening up the star points and connecting the inner end of phase *A* to the outer end of phase *B* or *C*, the inner end of phase *B* to the outer end of phase *C* or *A*, and the inner end of phase *C* to the outer end of phase *A* or *B*. If the star diagram is not symmetrical with respect to the three phases it is never advisable to change over to delta.

Wave Windings.—In a wave winding, correspondingly placed conductors under adjacent poles are connected in series, the circuit proceeding from pole to pole one or more times around the core, and not forward and back upon itself as in a lap winding. The circuits are then interconnected in such a manner as to give the requisite phase relations. The total number of these circuits must be a multiple of the number of phases and is ordinarily twice the number of phases.

Due to certain limitations, this type of winding is not used to as great an extent as the lap or the concentric windings. Its use on small motors is limited to phase-wound secondaries. Since a two-phase secondary would require four collector rings, or if connected for a three-wire system would overload one of the rings, while a three-phase winding requires but three rings, the latter only is general for such applications.

The number of slots for this type of winding (plus or minus one) is so chosen as to be divisible by the number of pairs of poles or preferably by the number of poles. If plus one, it is said to be a progressive winding, since after traveling once around the circuit it returns to the starting slot plus one. If minus one, it is said to be retrogressive since the circuit returns the winding to the starting slot minus one.

With this arrangement it is impossible to balance the phases exactly, but the effective unbalancing is small with a large number of slots. Since an unbalanced three-phase winding is less objectionable than a two-phase winding, the scheme is used

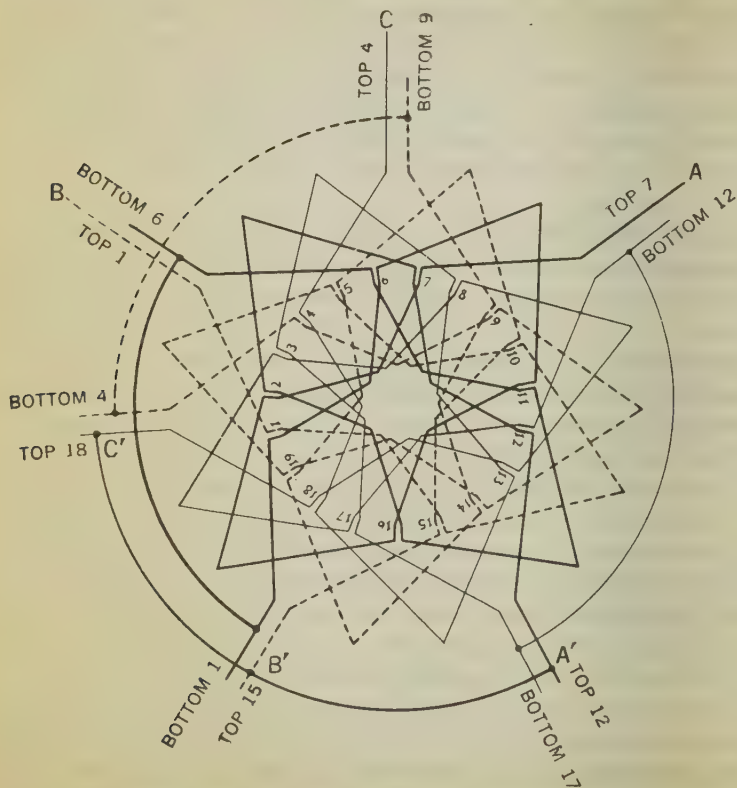


FIG. 12.—Wave winding, three-phase, four poles, 19 slots, 19 coils, two coils per slot, throw 1-6, unbalanced phases. Connected in *series star*. First series begins bottom slot 6, ends top slot 12; second series begins bottom slot 17, ends top slot 4; third series begins bottom slot 9, ends top slot 15; fourth series begins bottom slot 1, ends top slot 7; fifth series begins bottom slot 12, ends top slot 18; sixth series begins bottom slot 4, ends top slot 1.

chiefly for the former. Since an unbalanced winding is less detrimental in a secondary circuit than in a primary, the principal application of this type of winding has been in secondary circuits.

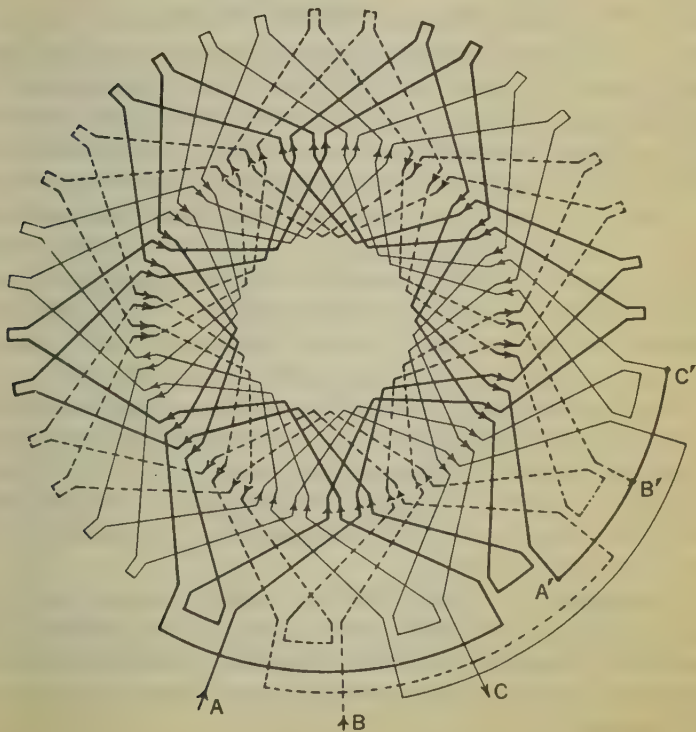


FIG. 13.—Wave winding, three-phase, six poles, 36 slots, 36 coils, two coils per slot, throw 1-7. Connected in *series star*.

Fig. 12 represents a two-conductor per slot winding, such as a bar and end conductor type, but is equally applicable to strap or wire wound coils of two or more series turns per coil, in which case the connector on the rear end of the coil takes care of itself and the front end is connected in a manner similar to the sketches. There are several methods of connecting up the three phases, depending on the desired voltage.

The principal connection is indicated in fig. 12. By connecting the end of each series circuit to the beginning of the next and taking off leads at the point of connection of series 1-2, 3-4, 5-6, instead of the connections between the series shown in fig. 12, a connection is obtained for one-half voltage.

An 86% voltage tap in terms of the connections shown in fig. 12 is secured by connecting the end of series 2 to the beginning of series 3, the end of series 4 to the beginning of series 5, the end of series 6 to the beginning of series 1. To connect in star join the ends of series 1, series 3, and series 5, and take off leads at the beginning of series 6, series 2, and series 4.

Since this connection reduces the voltage without increasing the cross section of the copper the winding will be less efficient on account of higher copper loss for the same output. This is also true of the 50% voltage connection, since for the same output the current density in the windings is 15% greater than for the full voltage connection.

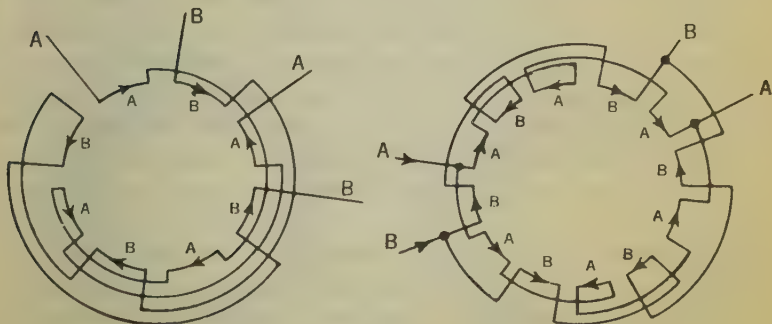
It is possible to lay out a winding which is balanced by choosing a number of slots which are divisible by the product of the number of phases by the number of poles. For such a winding the circuit returns to the starting slot after passing once around the armature.

It is then only necessary to supply a special connector to join it to the conductor in the starting slot plus or minus one. This winding thus embodies the best features of both types as, for

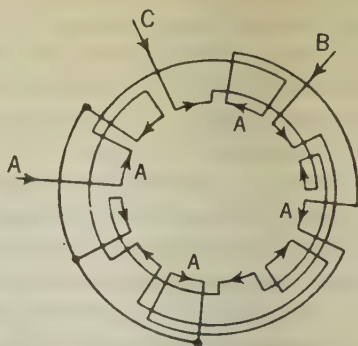
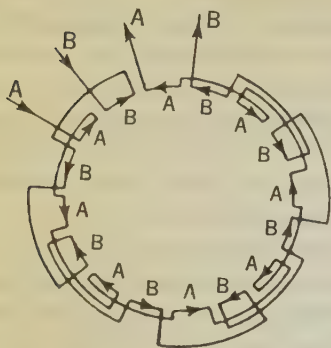
example, an electrical balance and a minimum number of special connections, which means a very compact and easily-assembled winding. By inspecting fig. 13, it is evident that the number of special connections is comparatively small with respect to the number of coils. This feature is more pronounced as the number of poles is increased.

Hence, a winding for a large number of poles 12 to 40, the number of special connections become insignificant.

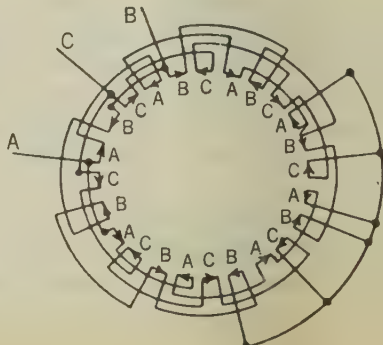
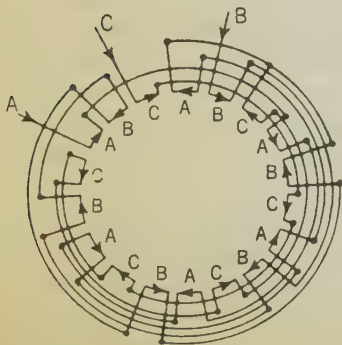
Figs. 14 to 19 show typical diagrams of four-, six- and eight-pole machines, one and two circuit, long and short jumper and in the case of the three-phase diagrams, star and delta connections. With the knowledge of the foregoing diagrams these should not present any difficulties.



FIGS. 14 and 15.—Typical winding diagrams. Fig. 14 shows the winding of a two-phase, four-pole machine, one circuit long jumper, while fig. 15 shows the winding of two-phase, six-pole machine, two circuits, short jumper.



FIGS. 16 and 17.—Showing winding diagrams of a two- and three-phase machine, respectively. Fig. 16 is an eight-pole machine, one circuit diagram, connected short jumper, while fig. 17 is a four-pole machine, one-circuit, short jumper, *star connected*.



FIGS. 18 and 19.—Winding diagrams of two- and three-phase machines, having six and eight poles, respectively. Fig. 18, one-circuit, long jumper; fig. 19, two-circuit short jumper. Both are *star connected*.

CHAPTER 24

Winding Connections for Speed Changes of Induction Motors

General.—Since the synchronous speed of an induction motor depends upon the frequency of the supply voltage and the number of poles in the motor, the only method of obtaining a change in speed is to change either or both of these factors.

To change the frequency involves expensive additional machinery such as frequency converters, while the change of the number of pairs of poles requires only additional connections to the motor control panel. It is this latter method of speed control which is most generally used in effecting a speed change in induction motors. It should be noted, however, that only a definite speed change will be obtained for each variation in the number of poles connected.

As the number of various definite speeds desired increases, the expense of the control equipment, as well as that of the motor will increase. Therefore two speed motors with a single winding are most commonly employed, because they require few leads and a simple means of control. Usually two speeds are obtained from one winding, so that if the motor is a four speed one, it will have two separate windings, and if it is a three-speed motor it will have three separate windings.

The wound-rotor motor, with resistance inserted in the secondary circuit, is most commonly used for speed variation. This type is suitable where the speed range required is small; where the speeds desired do not coincide with a synchronous speed of the line frequency; or where the speed must be gradually or frequently changed from one value to another.

The wound-rotor motor also gives high starting torque with a low current demand from the line, but it is not efficient when used a large proportion of the time at reduced speed, since power corresponding to the percent drop in speed is consumed in the external resistance without doing any useful work.

The wound-rotor motor can operate at any speed from its maximum full-load speed down to almost standstill. Speed reduction below one-half is not recommended, however, on account of both the poor speed regulation (the no-load speed is always synchronous speed) and the increased heating of the motor due to the decreased ventilation.

With the stator windings arranged to give several synchronous speeds, the stator can be used either with a squirrel-cage rotor to give several fixed speeds, or with a wound rotor to give speed regulation between the several speeds determined by the stator winding.

The simplest arrangement is a separate stator winding for each speed desired. With this arrangement each speed is practically independent of the others with a rating and performance to suit the application. Elevator motors require this type of winding, as it is undesirable to lose control of the car when changing from one speed to the other, which is necessary on reconnected windings. The separate windings allow the second winding to be connected to the line an instant before the first one is disconnected so that the motor is never without torque.

Aside from the application, the type of winding to be used is determined mainly by the speeds, and the ratings required at the various speeds. Where the speeds desired have a ratio other than two to one, a separate winding is practically always used for each speed.

If the difference in the two speeds is slight, the same throw is used in both windings and the coils are wound into the slots in the same manner as for an ordinary winding having two coil sides per slot, except that coils of each winding are placed in the slots alternately with leads of the two windings on opposite sides of the core.

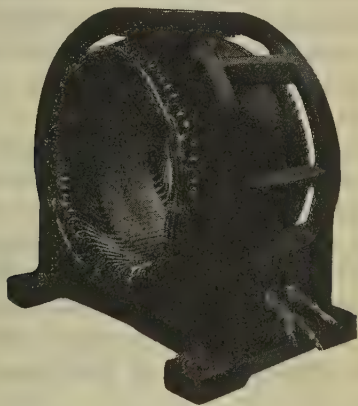


FIG. 1. —Showing stator winding of typical wound-rotor induction motor. (Courtesy General Electric Co.)

Since, in general, the coils of the two windings do not have the same cross-section, in order to use the slot space most effectively, it is necessary to have a coil throw such that each slot contains one coil side from each winding—this being accomplished by using an odd coil pitch, or a coil throw of 1 and

(an even number). Each winding is connected for a definite number of poles and voltage is applied to one winding at a time, depending on the speed desired. The other winding is left open and there is no voltage at the terminals.

Where the speeds are widely different, and the throw of the coils for the different speeds could not be the same, one winding must always be put below the other.

The winding nearest the air-gap is usually for the lowest speed, as this position has lower reactance, which is a necessity for a good design of a low-speed motor. The high speed winding is put in the bottom of the slot, as it normally has sufficient margin to allow it to occupy the less favorable position.

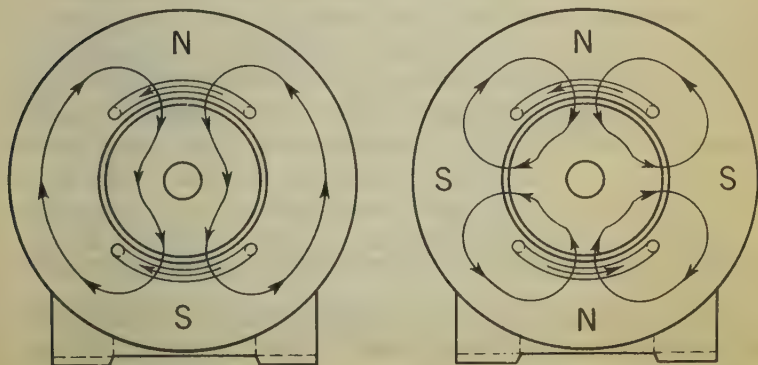
With this arrangement any number of speeds can be made, but usually not more than four speeds are attempted, as a greater number would involve large amounts of inactive copper and very deep slots.

Instead of using separate windings for each speed, special connections and extra leads are often brought out from a single winding so that external connections can be made to give several speeds. In a motor with a single winding, and speed ratios other than two to one, the complicated connections, the number of leads and the cost of the special control, which sometimes includes transformers with as many leads as the motor, have limited the manufacture of this type to a very few installations.

Motors with a single winding and a two-to-one ratio are in more general use on account of the few leads and simple control without transformers and are the only ones considered in this chapter. The fundamental idea in this type of motor is the consequent pole, by which the number of poles is doubled by a certain connection. In order to obtain a clear understanding of this, assume a two-pole, single-phase induction motor with two coils.

For normal operation, the coils are so connected that one coil produces a north pole and the other a south pole. These coils may be in series or parallel, the only condition being the direction of current. The flux with this connection crosses the air-gap to the rotor under the north pole and after crossing the rotor returns to the stator under the south pole, as shown in fig. 2.

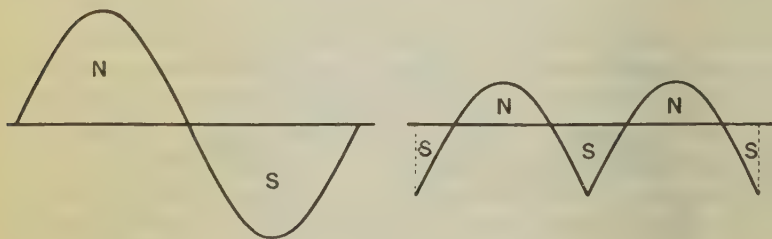
Now, if the connections to the south pole coils are reversed, it will produce a north pole also. With this condition, the flux from the first north pole cannot return to the stator at the same place as before, since the second coil opposes it instead of assisting it. The flux is now entering the rotor at two opposite points, and, therefore, can only return midway between these points, that is, at right angles to the axis of the coils, as shown in fig. 3.



FIGS 2 and 3.—Diagrammatic views of two-pole single-phase induction motor with two stator coils. Fig. 2 shows motor connected for normal two-phase operation; fig. 3, consequent pole connection for double the normal number of poles.

Since the area where flux passes from stator to rotor is a north pole and from rotor to stator a south pole, there are now two north poles produced by the coils and two south poles produced by the flux returning to the stator midway between the north poles or a total of four poles. Thus, if the windings and connections are made properly, the number of poles may be doubled by changing the direction of the current in one half of the windings.

Another explanation of this action is shown in figs. 4 and 5. Fig. 4 shows the sine-shaped field of a two-pole motor, one pole being north, drawn above the base line and the other south, drawn below. In fig. 5 the north pole is the same as before, but the south pole is reversed so that it is the same as the north pole.



FIGS. 4 and 5.—Sine-shaped field of two-pole motor, and effect on field when reversing one pole of two-pole motor.

Since any magnetic circuit is a closed circuit, any line of force which goes out of the stator under a north pole, must return and in so doing acts as a south pole. In other words, the same number of lines of force return under a south pole as went out of the stator under a north pole; or, in fig. 5, the base line must be moved up until the areas between the curve and the base line

are equal. With the base line moved up, the two areas above the base line are north poles and the two areas below the base line are south poles or a total of four poles.

Any stator core can supply a certain torque, measured in pounds at one foot radius, and a motor wound for a two-to-one change in speed would be capable of at least double the horse-power rating at the high speed. At the higher speed, the ventilation is much improved over the lower, and it is usually possible to obtain three times the horse-power rating of the low speed, if the connections be made so as to give good torques at the increased horse-power.

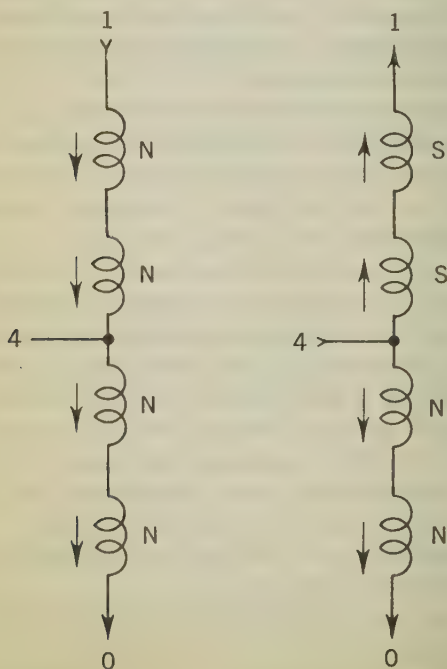
To give the higher torques and also the increased copper area to carry the large horse-power, three-phase windings are connected in *parallel star* for the *high speed* and in *series, either star or delta*, for the *low speed*. Two-phase motors are connected in parallel and series, respectively.

One phase of a four- and eight-pole motor combination, shown in figs. 6 and 7, is arranged for a parallel connection on the high speed and for series connection on the low speed. The four coils are so connected that when lead 4 is left open and current enters lead 1 and goes through the coils to lead 0, four north poles are produced which, with the four consequent south poles produced as explained previously, gives a total of eight poles. For the high speed, high rating, the current is put in at lead 4 and the lead 1 is attached to lead 0. This gives a parallel connection and a reversal of the current in the two poles between leads 1 and 4.

The coils now produce two north poles and two south poles or a total of four.

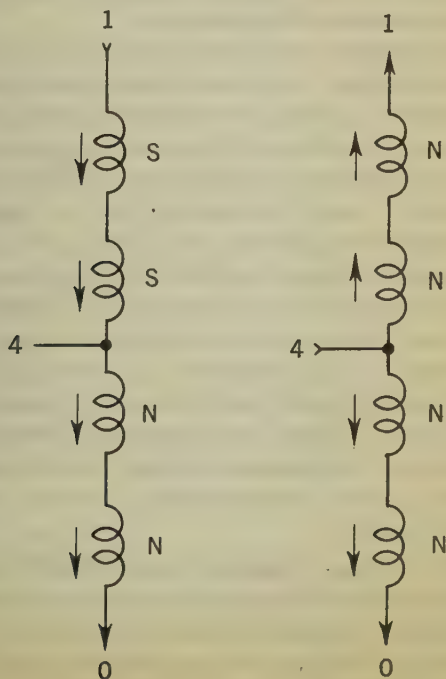
This is the usual connection as most applications require more horse-power at the higher speed, but there are a few applications where the same horse-power is required at both speeds. This means that at low speed double the torque of the

high speed could be produced, and since any core can deliver only a certain torque, the size of the machine is determined by the torque at low speed. At high speed, the torque required is one-half of that which the motor is capable of developing, so that at this speed the motor is very much under-rated and the motor cost is high.



FIGS. 6 and 7.—One-phase of constant torque winding for either four or eight pole operation. Fig. 6 illustrates series connection for low speed, and fig 7 parallel connection for high speed.

The connections used for constant horse-power can best be explained by comparison with the constant torque connections in figs. 6 and 7. To develop the high torque at the low speed, a strong field is necessary, so the windings are connected in parallel. This means that twice the voltage per turn is impressed on the winding which, if there were no change in speed, would require twice the flux to produce the corresponding counter *e.m.f.*



FIGS. 8 and 9.—One-phase of constant horse-power winding for either four or eight poles. Fig. 8 shows series connection for high speed and fig. 9 parallel connection for low speed.

Since, however, the speed is only half as great, a flux of approximately four times that produced with the high-speed connections is obtained, the exact value of this flux depending on the relative chordings with the two connections. The magnetic circuits must, of course, be large enough to carry this flux, so that the low-speed winding, as previously stated, is the limiting one in the design of the motor. The torque is proportional to the product of this flux, and the secondary current. At the high speed the torque required is low, so the series winding gives sufficient field strength.

In order to develop four poles with the series connection in fig. 6 the connections to the two north poles between leads 1 and 4 are reversed, so that current flowing from lead 1 to lead 0 produces two south poles and two north poles, as in fig. 8.

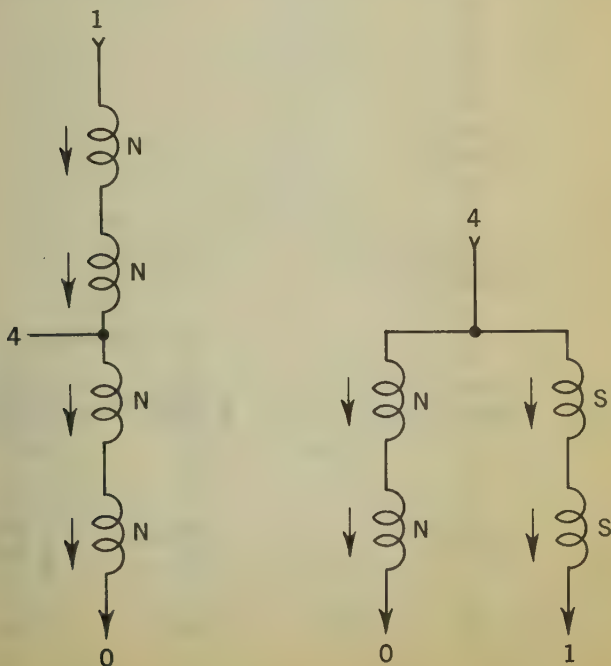
Under these conditions, with current entering at lead 4 and leaving at leads 1 and 0 in parallel, the two upper fields are reversed. They then produce two north poles in addition to the two lower north poles in which the direction of current is not changed, or a total of four north poles, which with the four consequent south poles, give an eight-pole motor.

In all consequent pole diagrams, it is much clearer to change each phase as a unit and make the connections to the other phases afterwards. Schematic diagrams show the windings in such relation that the measured distance between any two points is a measure of the voltage existing between corresponding points on the motor.

In fig. 6 the voltage is applied between leads 1 and 0 so that the voltage on each coil is proportional to its length. Now, in fig. 7 the voltage is applied to lead 4 and lead 1 is jointed to lead 0. There is then no voltage between leads 1 and 0 and in the schematic diagram, they should coincide. Since 4 is a common lead, points 1 and 0 are brought together by swinging

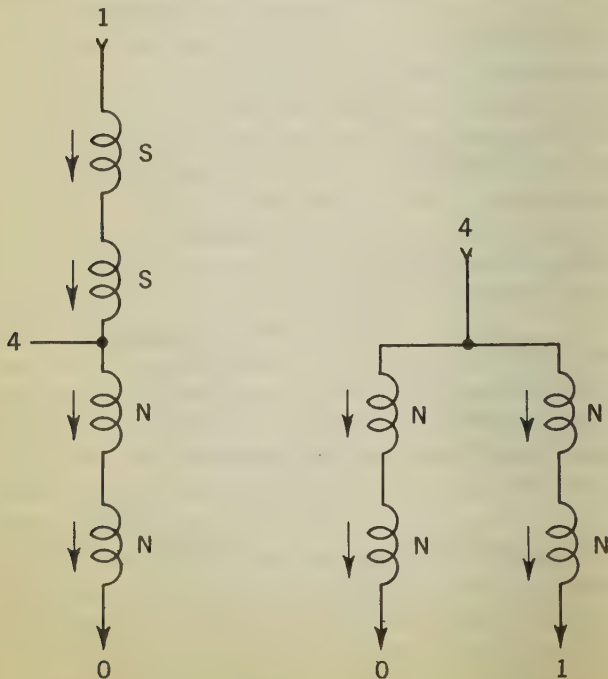
the section 1 to 4 around 4 until leads 1 and 0 coincide. The schematic diagrams for figs. 6 to 9 are shown in figs. 10 to 13. The various combinations of phases and connections in most common use are described in the following.

Three-Phase, Series-Star Low Speed; Parallel-Star High Speed.—In figs. 14 to 21 the coil groups marked A_2 , B_2 and C_2 have all the north poles, while coil groups A_1 , B_1 and C_1 have all the south poles. Fig. 14 shows the low speed connection.



FIGS. 10 and 11.—Shows schematic diagrams for figs. 6 and 7.

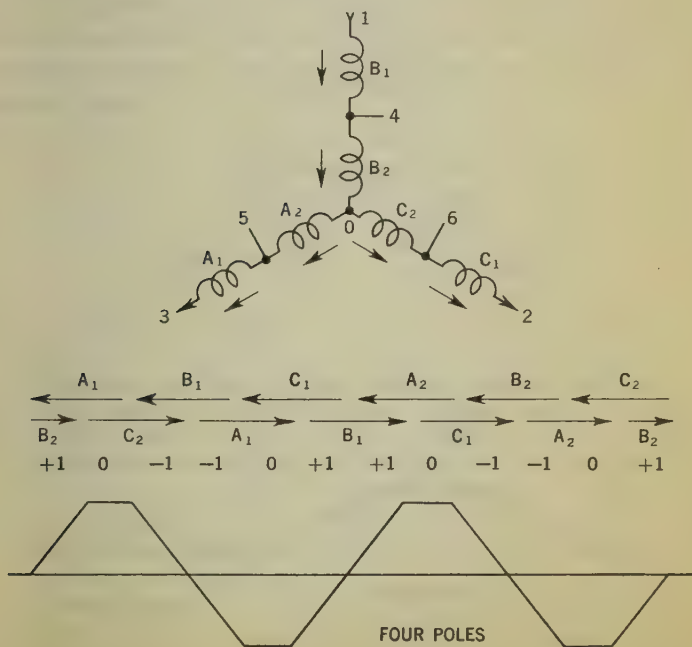
For the particular instant when the instantaneous value of current is maximum in the *B* phase and one-half value in the opposite direction in phases *A* and *C*, fig. 15 shows the relative directions of the currents in the coil groups, assuming the coils to be wound with one-half pitch with reference to the normal or high-speed connection. Fig. 16 shows the resultant amperes in the slots, assuming that the *B* current is 2 and the *A* and *C* currents 1 and those to the right as positive and those to the left as negative.



FIGS. 12 and 13.—Shows schematic diagrams for figs. 8 and 9.

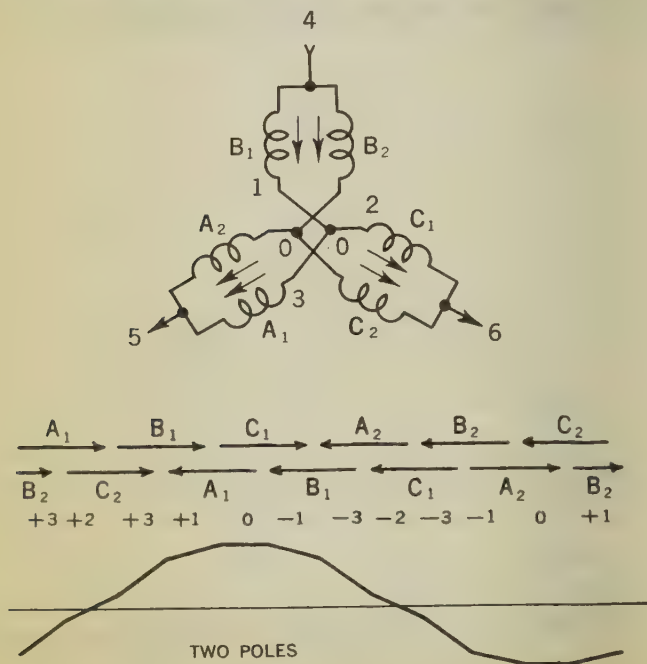
left as negative. Fig. 17 shows the ampere-turns of fig. 16 plotted to show the fields. This shows two above the base line and two below, or a four-pole motor.

Fig. 18 shows the high-speed connection with the same winding and the same instantaneous values of current. Figs. 19 to 21 show the same values as in figs. 15 to 17 except that the field produced in this case has only one field above the base line and one below, resulting in a two-pole motor.



FIGS. 14 to 17.—Illustrates series-star connection for consequent poles.

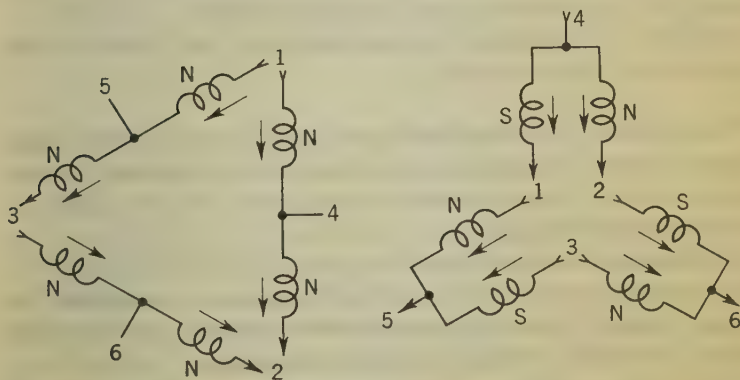
This connection gives approximately 50% more maximum torque in pounds at one foot radius at high speed than at the low speed, and is used where the rating desired is approximately three to one or where extra high torque is required at high speed. Usual applications are for centrifugal pumps and blowers and oil well pumping motors.



FIGS. 18 to 21.—Parallel-star connection for normal number of poles.

Three-Phase, Series-Delta Low Speed; Parallel-Star High Speed.—In figs. 22 and 23 the phases have been separated to make the transition clearer. Fig. 22 shows the lower speed connection with the line on leads 1, 2 and 3 and the leads 4, 5 and 6 open. This gives the delta connection with the groups in series, both producing north poles or double the normal number of poles.

Fig. 23 shows the high-speed connection with the line on leads 4, 5 and 6 and the leads 1, 2 and 3 short-circuited. Taking each phase separately, the current in one half of the groups is unchanged and in the other half is reversed. This gives the parallel connection and one-half the number of poles, as explained before.



FIGS. 22 and 23.—Illustrating method of obtaining constant torque or two-to-one ratio of horsepower. Fig. 22 illustrates series-delta connection for low speed and fig. 23 parallel-star connection for high speed.

Each of the phases should be changed separately, being careful not to change the angle of the part which has current in the same direction as before. Sections which have the current reversed are doubled back on the ones which do not change. Then keeping the same angle, the sections are moved until the shorted leads 1, 2 and 3 come together, giving a diagram as shown in fig. 23.

This connection gives practically the same maximum torque in pounds at one-foot radius at both speeds, that is, a rating in horse-power of approximately two to one, and is used for applications demanding constant torque.

Three-Phase, Parallel-Star Low Speed; Series-Star High Speed.—This connection is just the reverse of the three-to-one rating and would give a very high pullout torque on the low speed, that is, more than the decrease in speed.

Applications requiring this type are scarce and there is little demand for this connection.

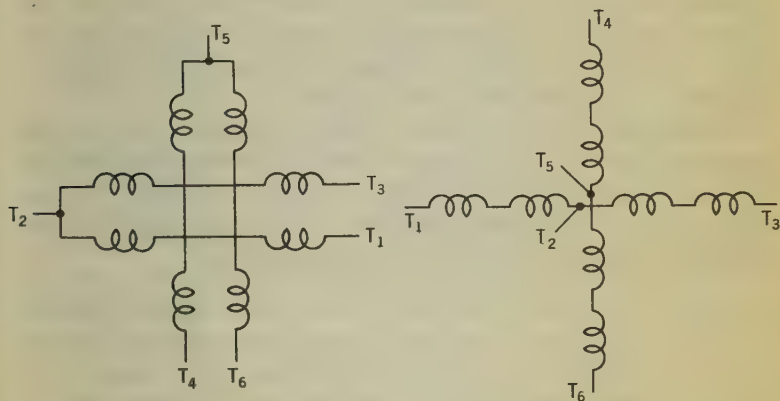
Three-Phase, Parallel-Star Low Speed; Series-Delta High Speed.—This connection gives practically constant horse-power, that is, the maximum horse-power of both speeds is approximately the same.

Applications which demand this are machine tools, where a much heavier cut is taken at the lower speed, requiring increased torque. The diagrams for this connection are the same as figs. 22 and 23, with 22 and 23 interchanged.

Two-Phase Connections.—Two-phase connections for two speeds are shown in figs. 24 and 25. The series low speed, parallel high speed connection gives the same torque characteristics as the series and parallel star connection on three-

phase, that is, a horse-power rating at the high speed approximately three times the horse-power at the low speed.

The two-phase, parallel low-speed, series high-speed connection gives as does the corresponding three-phase star connection, the greater horse-power and a very high pull-out torque at the low speed.



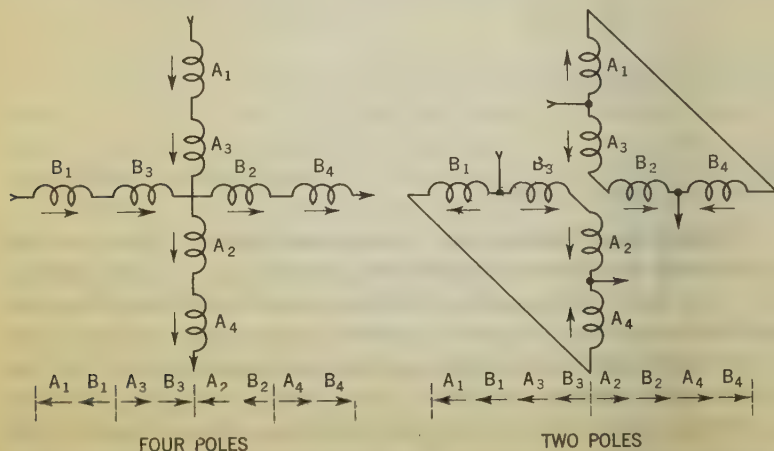
FIGS. 24 and 25.—Two-phase winding arranged for two speeds. Fig 24 shows parallel connection and fig. 25 series connection.

Distribution Factor.—In three-phase motors, the coils in each pole are divided into three groups, one for each phase. In two-speed motors, this division is made so that when the effective number of poles is doubled, each phase group covers two-thirds the pole pitch, instead of one-third as for the high-speed number of poles. This change decreases the distribution factor of the windings for the consequent pole connection from 0.955 to 0.827, reducing the effectiveness of the winding to 86% of its value for the normal pole number.

In two-phase machines the width of the phase group is increased from one-half the pole pitch to the whole pole pitch. This reduces the distribution factor from 0.90 to 0.636 and consequently the effectiveness is lowered to 70% of its former value.

This loss in effectiveness can only be avoided by dividing the coils into phase groups corresponding to the low speed and shifting the groups to different phases as required for the different speeds. On three-phase motors, this requires too many connections and too complicated control to make it practical. Also the gain is not as great.

In two-phase motors, however, only one-half of the coils of each phase need to be changed to the other phase and this can be done with only 12 leads, as shown in figs. 26 and 27. These diagrams show a series connection for the low speed and the phases are marked *A* and *B* for this connection.



FIGS. 26 and 27.—Two-phase series low-speed connection and parallel high-speed connection, with interconnected phases, respectively.

For the high-speed connection, the coils are put in parallel and one-half of each phase is shifted to the other phase. This makes the winding equally effective at both speeds and avoids the 30% loss in winding efficiency.

Chord Factor.—When the motor connections are changed from normal to consequent poles, the pole width, and hence the chord factor, is materially changed. It is customary to chord the windings approximately one-half for the high-speed connection, giving full pitch on the low-speed connection, as this usually produces the best torque and flux conditions. This gives chord factors (the chord factor is the sine of one-half the electrical angle spanned by the coil) of 0.70 and 1.00.

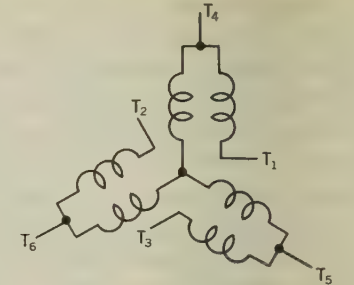
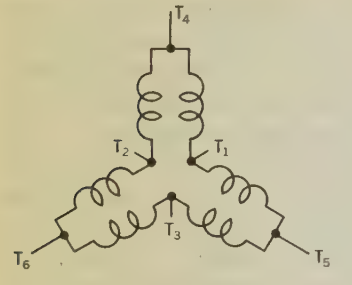
Chording below one-half is not recommended. If the winding is chorded two-thirds on the high speed connection, the chord factor will have the same value (0.866) on both connections. As it is not always possible to obtain the exact chording desired with a given number of slots, the winding is chorded something between one-half and two-thirds, for either a three-phase or a two-phase winding.

The marking of leads for several of the connections described previously has been standardized so that motors of different manufacture will have the same terminal markings. Some of these are shown in figs. 28 to 31.

Rotor Windings.—The rotors used with these stators may be either squirrel-cage or wound rotors. Squirrel-cage rotors have no definite poles and will operate at the speed determined by the stator field. The resistance of bars and rings must be proportioned to give good starting torques at both speeds.

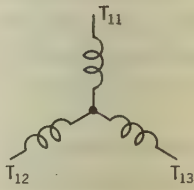
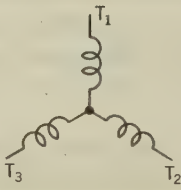
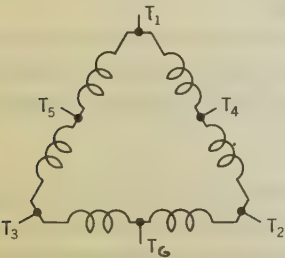
Wound rotors should have the pitch of the coils approximately the same as the stators, and the connections should be

such as to give the same number of poles, as the stator at all times. If the connections to the rotor tend to produce a different number of poles than that produced by the stator at any time, no torque will be produced and the motor will not run.



SPEED	L ₁	L ₂	L ₃	
LOW	T ₁	T ₂	T ₃	T ₄ T ₅ T ₆ OPEN
HIGH	T ₄	T ₅	T ₆	T ₁ T ₂ T ₃ SHORTED

SPEED	L ₁	L ₂	L ₃	
LOW	T ₁	T ₂	T ₃	T ₄ T ₅ T ₆ OPEN
HIGH	T ₄	T ₅	T ₆	T ₁ T ₂ T ₃ SHORTED



SPEED	L ₁	L ₂	L ₃	
LOW	T ₄	T ₅	T ₆	T ₁ T ₂ T ₃ SHORTED
HIGH	T ₁	T ₂	T ₃	T ₄ T ₅ T ₆ OPEN

SPEED	L ₁	L ₂	L ₃	
HIGH	T ₁	T ₂	T ₃	
LOW	T ₁₁	T ₁₂	T ₁₃	

FIGS. 28 TO 31.—Illustrating lead markings for various three-phase two-speed connections.

Different connections of the rotor circuit, if for the correct pole combinations, have no influence on the torque characteristics of the motor, so the various connections for the different pole numbers as explained for the stator connections only change the open-circuit voltages of the rotor circuit. The connection chosen for the rotor is that one best suited to the controller and the application.

An induction motor at standstill is merely a polyphase transformer. The voltage appearing at the collector rings is determined by the number of series conductors and the connection used for the different speeds.

Thus, for example, a motor having 252 series conductors per leg and when operating on the high speed had an induced rotor voltage of one volt per conductor. When connected for the low speed, it had an induced rotor voltage of 0.8 volt per conductor. If the rotor is connected parallel-star for the high speed and series-star for the low speed, the high-speed, open-circuit secondary voltage would be 252 conductors divided by 2 for the parallel circuit times 1 volt per conductor or 126 volts per leg or 220 volts per terminal.

On the low speed, the secondary voltage would be $252 \times 0.8 \times \sqrt{3}$ or 350 volts. If the rotor is connected parallel-star high speed and series-delta low speed, the high-speed voltage is the same as before, but the low-speed voltage will only be 252×0.8 or 200 volts.

The foregoing combinations may be reversed, that is, for the high speed connection the rotor in series-star and for the low speed in parallel-star. The voltages are then $252 \times 1 \times \sqrt{3}$ or 440 volts for the high speed, and $252 \times 0.8 \times \sqrt{3}/2$ or 175 volts for the low speed.

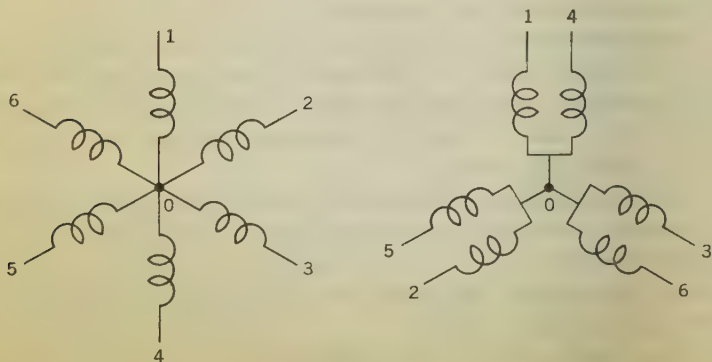
The second combination reversed gives the series-delta for the high speed and parallel-star for the low speed or voltages of

$252 \times 1 = 252$ volts on the high speed and $252 \times 0.8 \times \sqrt{3} / 2$ or 175 volts on the low speed.

A combination which does not require any pole changing connection in the rotor circuit joins each of the three phases together at their midpoint as shown in figs. 32 and 33, producing a six-phase star connection on one pole connection and a parallel connection on the other. In each phase, all the north poles are in one half and the south poles in the other half, just as for the primary connections.

The resistance should be balanced in all phases on all points to prevent unbalanced currents and consequent burnouts.

If the six-phase connection is used for the high speed and the parallel three-phase for the low speed, the voltages would be, for the previous example, $252 \times 1 = 252$ volts six-phase for the high speed and $252 \times 0.8 \sqrt{3} / 2 = 175$ volts three-phase for the low speed. With the connections reversed, the voltages would be $252 \times 1 \times \sqrt{3} / 2 = 220$ volts three-phase for the high speed and $252 \times 0.8 = 200$ volts six-phase for the low speed.



FIGS. 32 and 33.—Rotor connection which adjusts itself to the number of primary poles without mechanical pole changing devices. Six slip rings are required for this connection.

Summarizing these voltages in Table I, it is seen that a large variety of secondary characteristics can be obtained and the one best suited to the control and the application can be chosen.

TABLE I—ROTOR VOLTAGES

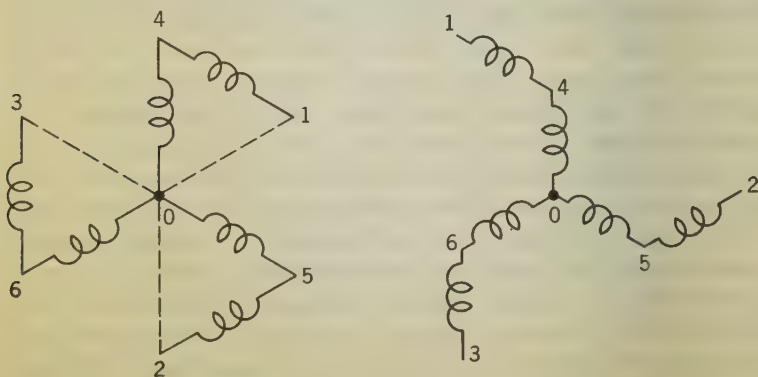
High Speed			Low Speed		
Connection	Sec. Volts	Phases	Connection	Sec. Volts	Phases
Parallel star	220	3	Series star	350	3
Parallel star	220	3	Series delta	200	3
Series star	440	3	Parallel star	175	3
Series delta	252	3	Parallel star	175	3
Series star	252	6	Parallel star	175	3
Parallel star	220	3	Series star	200	6

All of these connections require six collector rings and this is the only way to obtain the full benefit of the winding. However, if the rotor copper can be increased, or the normal amount need not be fully utilized, there is a connection which permits the use of only three rings. This is accomplished by combining half of one phase with half of another phase, as shown in figs. 34 and 35, the halves nearest the neutral having all one kind of poles and the outer halves having the other kind.

Thus, in figs. 34 and 35 the half phase 1-4 contains the south poles and the half phase 5-0 the north poles. When the stator connections are changed from one pole number to the other, the direction of the voltage induced in the outer legs is reversed, and the half phases 1-4, 2-5 and 3-6 swing around 180° and take the different positions shown. The terminal voltage is proportional to the geometric distance between the points 1, 2 and 3.

If fig. 34 is used for the high speed and fig. 35 for the low speed, the voltage will be $252 \times 1 \times \sqrt{3} / 2$ or 220 volts for the high speed and $252 \times 0.8 \times \sqrt{3} \times \sqrt{3} / 2 = 300$ volts for the low speed.

If fig. 35 is used for the high speed and fig. 34 for the low speed, the voltage will be $252 \times 1 \times \sqrt{3} \times \sqrt{3} / 2 = 378$ volts for the high speed and $252 \times 0.8 \times \sqrt{3} / 2 = 175$ volts for the low speed. This connection is not desirable, as in fig. 34, only one-half the voltage induced appears at the collector rings. At one-half voltage the current for the same output must be double and since the circuit is not paralleled, but left in series, the losses in the copper are four times what they would be in a winding used to the best advantage. Its only advantage is the use of three collector rings instead of six, but this is offset by either double the necessary copper or four times the rotor copper loss.



FIGS. 34 and 35.—Another rotor connection requiring no pole changing device. Here only three slip rings are needed, but copper is used less efficiently because the currents are out of phase with the induced voltage.

CHAPTER 25

Field Coils for A.C. and D.C. Machines

General.—It is a well known fact that field coils in generators and motors are subjected to mechanical stresses from various causes. These are vibration, magnetic reaction between field poles and armature, heating due to load currents, centrifugal action (in rotating type field machines) stresses caused by bringing the machine up to speed, etc.

Thus the coils must be rigidly braced, and suitably insulated to prevent insulation breakdowns between the turns. It should also be remembered that the voltage stresses consist not alone of the normal excitation voltage required to produce increased generator potential under overload conditions, but the excessive voltages occasioned by opening the field circuit without a discharge resistance, or by starting synchronous machines from the alternating current side.

Also, in addition to the electrical and mechanical characteristics which are absolutely essential for a field coil, other characteristics are very desirable. Although ventilation is essential to high efficiency and low cost, the ideal is to have bare copper exposed to air on all sides. This has been practically attained in certain types of series and strap coils for rotating field machines, and partially attained by strap wound shunt coils.

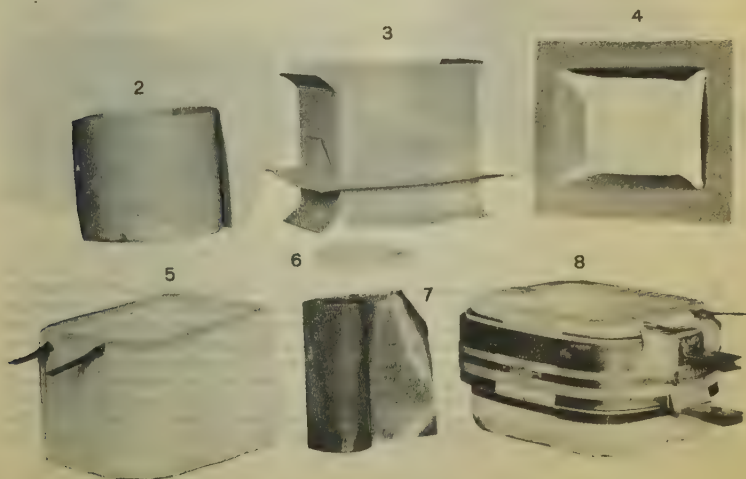
To meet the various requirements of voltage, size and conditions of service, a great variety of field coils are necessary. These may be most conveniently classified according to their method of winding.

Wire Coils.—Shunt coils for the smaller machines and for the higher voltages of fairly large machines are wound on moulds from round or square wire, which is nearly always cotton covered, tension being supplied by a form of friction brake on the reel from which the wire is taken.



FIG. 1.—Showing methods of assembly of shunt and interpole coils to frame in an integral horsepower direct current motor. (Courtesy General Electric Co.)

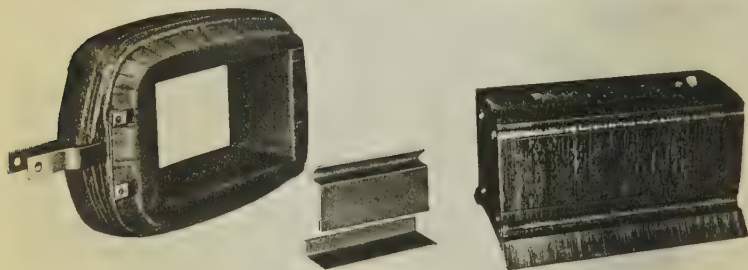
The end turns of each layer are usually supported by strips of tape or paper or by cord so placed as to lap around them and be held by the turns at the center of the coil. The wire is usually wound alternately right and left, much as thread is wound on a spool. Where the voltage per layer is high, this construction produces an excessive strain on the cotton insulation. In such cases a strip of paper or cloth is laid between the layers of wire for about half their length, or the end of the last turn is insulated and carried completely across the coil, all layers being commenced from the same end. Where coils are wound from heavy wire under considerable tension, the layers are protected from mechanical injury at the corners by strips of heavy paper.



FIGS. 2 TO 8.—Steps in manufacture of shunt field coil for direct current machine. In the illustration, fig. 2, is represented acetate-coated paper which is used in forming the main coil spool body; fig. 3, channel and one collar of spool body; fig. 4, collar of spool body; fig. 5, completely assembled shunt field coil; fig. 6, lead anchor which accurately locates and anchors terminal leads of shunt coil; fig. 7, varnished-cloth insulation; fig. 8, completely assembled compound wound coil. (Courtesy General Electric Co.)

The shape of the coil is frequently rectangular, with rounded corners, and with all the layers having approximately the same number of turns. Due to limitations of space, one edge of the coil may be beveled off, or the coil may be of a wedge shape by making the layers gradually shorter at one end, thus producing a stepped appearance. The coils are usually flat, but are sometimes rounded to conform to the shape of the field yoke. Such coils may be wound flat, and then pressed into the rounded form after winding, or may be wound on curved moulds especially if of heavy wire.

FIELD COILS

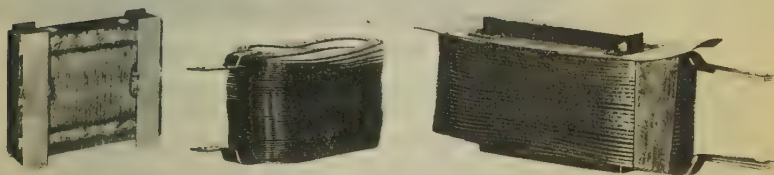


FIGS. 9 to 12.—Showing assembled shunt field coil and pole piece for direct current machine. The pole pieces of the main field poles are assembled from punched silicon-steel laminations and riveted together. The pole is held in place and in true alignment by two or more bolts through the frame. The field coil is assembled on the pole piece with spring-steel clamps between the pole and coil, and between the coil and frame. The spring action holds the coil tightly in place and prevents chafing of the insulation when the coil contracts or expands, because of the change in temperature. The surface of the pole which faces the armature is flared for distributing the flux across the air gap, to give stable operation over widespread ranges, and to promote satisfactory commutation under all normal operating conditions. (Courtesy General Electric Co.)

Joints in the wire are avoided whenever possible. When joints are necessary, they are of the wrapped or sleeve type and are as unobtrusive as possible. When suitable welding apparatus is available, an electrically welded butt joint is very satis-

factory on the larger sizes of wire and for copper strap. The joint is filed smooth, to remove all sharp corners, and taped so as to have the same insulating value as the rest of the wire.

The wire from which the coils are wound is liable to break off if subjected to vibration or bending. For this reason the ends are tied in place in the coil, and leads of stranded wire or strap copper are soldered on and brought to the outside of the coil. The lead from the inside is always crossed over the body of the coil, so that no connections are made close to the iron. The terminals for coils of large size are usually made from thin copper leaf to avoid bulkiness in crossing the coil.



FIGS. 13 to 15.—Showing assembly methods of typical commutating pole for a direct current machine. The pole pieces are of non-aging silicon-steel laminations with low residual magnetism. Laminations are welded or riveted together for perfect alignment. Coils are made of edgewise wound copper strip with enamel turn-insulation and are insulated from the pole by layers of laminated acetate paper. The coils are tied on the ends to prevent spreading and are held in place by brackets welded to the pole pieces. Large collars extend beyond the coils on the frame side, which provides additional protection from grounds. (Courtesy General Electric Co.)

Wire wound coils have generally been taped over the outside to provide mechanical protection to the coil. The present tendency, however, is to use as little outside covering as possible, in order to provide maximum ventilation, the coils being simply taped or corded in a few places to hold the strands in shape. In such cases extra insulation is supplied on the inside faces of the coil to protect it from grounds.

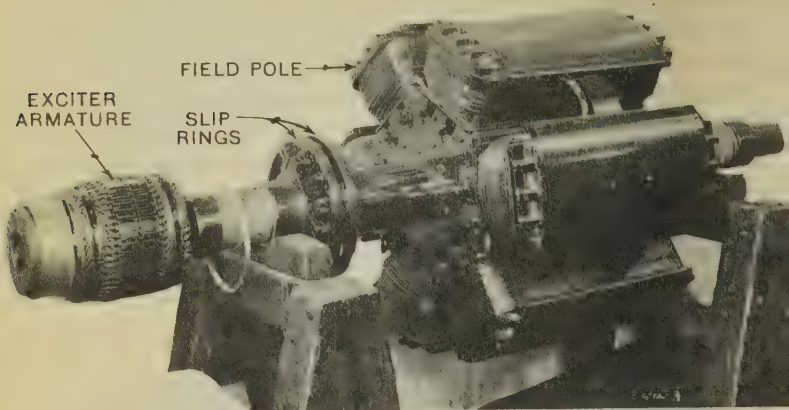


FIG. 16.—Showing field structure of typical six pole synchronous machine with salient pole construction. Note exciter armature mounted on machine shaft. (*Courtesy Electric Machinery Mfg. Co.*)

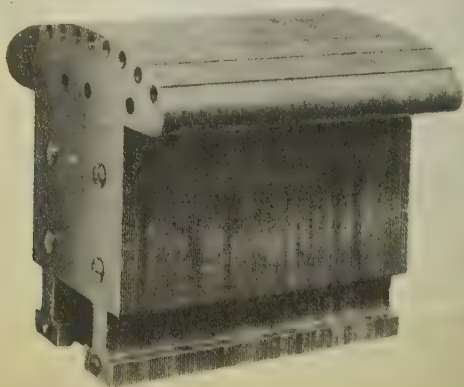


FIG. 17.—Showing assembled dovetailed field pole piece for large synchronous machine. (*Courtesy Electric Machinery Mfg. Co.*)

After being taped or tied the coils are placed in a tank in which the temperature is raised to a high degree and the air exhausted, thus removing the moisture and air from the coils. A moisture-proof insulating compound in liquid form at high temperature is run into the tank until the coils are immersed; air is then re-admitted to the tank under pressure, forcing the compound into all parts of the coils. The melting point of the compound is higher than any temperature the coils are liable to reach in operation, so that under normal conditions they form solid and absolutely water-proof units.

This compound is selected so as to be a good conductor of heat, and thus assists materially in maintaining a low operating temperature. A final coating of hard, water-proof varnish gives a good wearing surface which is easy to keep clean.

Flat Strap Coils —A very compact and solid construction for both series and shunt coils consists of bare strap copper wound in a mould with strips of paper or asbestos between the turns. This type is used very extensively for railway type series coils, and for shunt coils on large direct-current generators and rotary converters. On railway motors comparatively heavy copper is used with one or more strips of asbestos between turns. Two such coils, wound in opposite directions, are usually placed one above the other with insulation between. The inside ends are connected together, leaving the ends of the complete coil at the outside, to avoid the necessity for crossing the leads over the coil. One of the individual coils is frequently wound with fewer turns than the other, and the space between them filled with triangular-shaped insulating filler, producing beveled corners, thus allowing a better space factor inside the motor.

Railway type coils are tightly wound with heavy cotton tape, on account of the necessity for rigid bracing and protection against the constant jar and vibration. The leads are of heavy flexible cable in some types and in others are brought out to brass connectors, tied to the body of the coil. The coils are then vacuum impregnated and varnished.

This same type of construction with much smaller strap is used for shunt coils in large generators and motors. The coils are wound with paper between turns, tied with cord or tape, and impregnated. Several of the coils are then assembled, arranged alternately right and left, with insulation between the layers. The insulating spacers are so arranged that the air has free circulation through the coil parallel to the shaft only, so that the ventilating air is always fresh and cool. The inside and outside of adjacent coils are connected together, so that no crossing of the coil with leads is necessary, the ends of the complete coil coming at the outside end of the first and last layer of a coil with an even number of layers. Leads of flexible cable are usually soldered to the ends of the coil to prevent breakage. Insulating spacers prevent motion of the coils sideways on the poles, and the coils fit snugly against the pole pieces circumferentially, being separated therefrom by varnished paper or other suitable insulation.

Former Wound Coils.—The centrifugal strains on rotating field coils require special precautions to prevent chafing of the insulation. Specially reinforced wire-wound coils have proven very satisfactory, and are used in some cases. A coil wound with copper strap on edge, as shown in fig. 18, is ideal for this service, as it is practically incompressible, every turn being exposed to the air, so that the heat is readily dissipated.

These coils are wound on a form of special construction so that the copper strap may be bent edgewise without crinkling. They are then annealed, all rough edges being carefully removed. Asbestos strips are placed between the turns, together with a binding shellac. The entire coil is compressed in a press and is subjected to sufficient heat to drive off all moisture and combustible material.

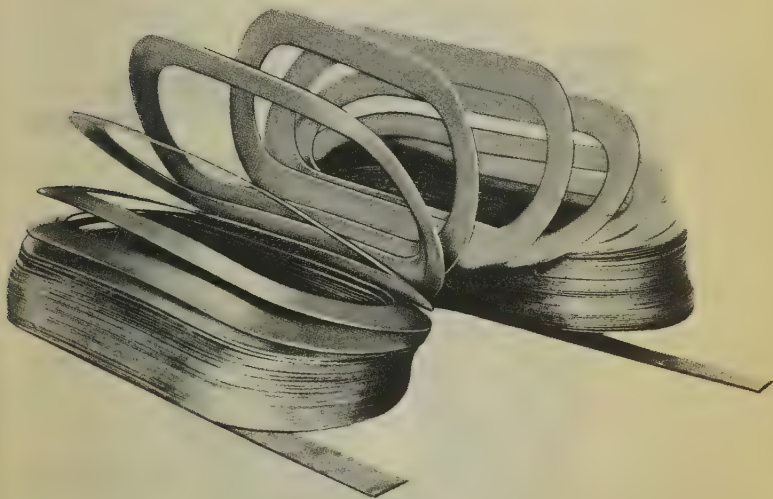


FIG. 18.—Showing flat edge-wound copper coil for field pole of large synchronous machine.
(Courtesy Fairbanks, Morse & Co.)

The coil is carefully insulated from the pole pieces, but no insulating material is placed over the outside. All the coils are formed alike, but have the leads arranged so as to be alternately right and left, the connections between coils coming alternately at the top and bottom, as shown in fig. 20.

Compound and interpole coils for direct-current generators and large motors are practically always of the strap-on-edge type, with adjacent turns separated by spacers.

No impregnation is necessary with the strap-on-edge coils of either open or closed type, as no absorbent insulating materials are used. They are shellacked to a black, glossy surface, which is moisture-repellent and is easy to clean.

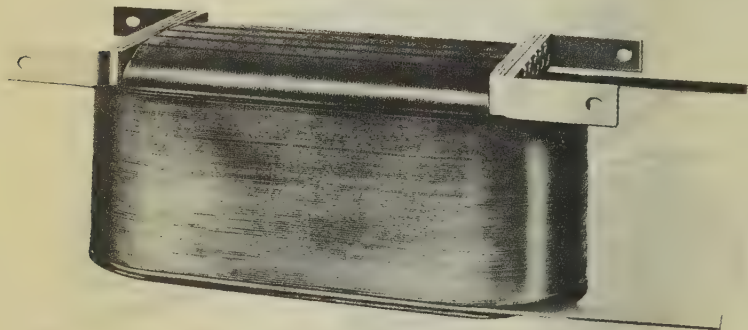


FIG. 19.—Showing complete field pole with damper winding in place. This field pole is part of a large synchronous machine. (Courtesy Fairbanks, Morse & Co.)

Field Excitation.—The field windings are usually built for low voltage, 120 or 250 volts D.C. In large power stations, the exciting current is usually supplied from a set of common bus bars employed for excitation only. Isolated machines on the other hand usually have their exciter mounted directly on the same shaft, as in fig. 16, or in some instances belt driven from the A.C. machine.

The direct current so generated is supplied through a pair of collector rings, which are insulated from the frame of the machine and to them the ends of the field coils are brought out and connected.

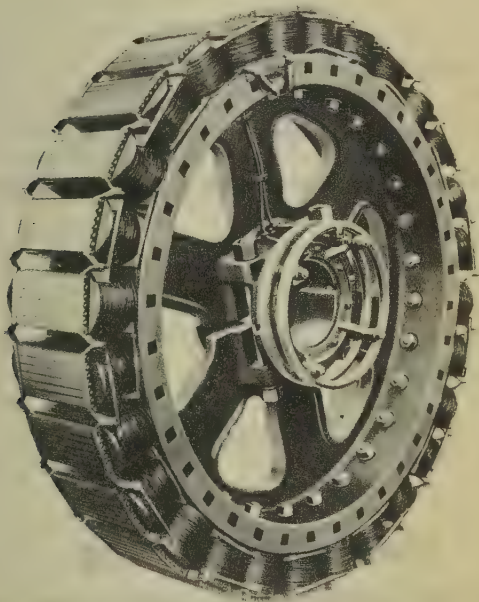


FIG. 20.—Showing construction details of rotating field for large low-speed synchronous motor. The rotor is equipped with field coils of the type shown in fig. 19 and with squirrel cage starting winding. The field coils are connected to the collector rings by means of heavy wires clamped to the rotor structure as indicated. (*Courtesy Fairbanks, Morse & Co.*)

Relations between Poles Frequency and Speed.—In any synchronous motor or generator the speed in revolutions per minute, at a certain frequency, depends upon the number of poles in the machine. This speed may be obtained by substitution of values in the formula:

$$f = \frac{Pn}{2 \times 60}$$

Where f = cycles per second.

P = number of poles in the machine.

n = revolutions per minute (*r.p.m.*).

If the foregoing equation is solved with respect to revolutions per minute, we obtain:

$$n = \frac{f \times 120}{P}$$

Thus the synchronous speed of 60 cycle, 6 pole machine would be equal to:

$$\frac{60 \times 120}{6} \text{ or } 1,200 \text{ r.p.m.}$$

Field Coil Testing

General.—Field coils furnish the excitation for the electrical machine and obviously the coils will not perform this function satisfactorily if they have shorted turns or grounds. In reconditioning rotating electrical machinery all field coils should be tested. Defective field coils often cause loss of power, roughening of commutator, rapid wearing away of brushes, overheating of armatures and premature failure of the machine.

The excitation value in magnetic flux lines is dependent upon the ampere-turn strength. If some of the field coil turns are short-circuited, there will be either a loss of ampere-turn strength or heavier than normal current may flow through the remaining effective turns to maintain approximately the normal magnetizing ampere-turn strength. Accordingly, our measuring stick in testing a field coil is the ampere-turn strength available for excitation.

The loss of a turn or a few turns does not always mean that a field coil must be replaced. A shunt field coil usually has a large number of turns of small wire, and the current flowing through its turns is small when compared to the total machine current. Series field coils and commutating field coils have few turns as compared to shunt field coils and carry the full machine current.

Excitation values and coil characteristics of a typical 10 *h.p.* 4 pole, 230 volt compound wound motor are as shown in Table I.

TABLE I

Item	Field Winding	Resist per Coil	Ampere Turns per Pair of Poles	Active Turns	Current in Amperes	I ² R Losses		Size Conductor in Circular Mils	% Excitation Loss in Shorted Coil
						Normal Coil	Shorted Coil		
1	Shunt	111	2,072	2,000	.518	29.8	.....	320	.....
2	Shunt (25 turns shorted out)	109.5	2,063	1,975	52	30	29.6	320	4/10 of 1%
3	Series	.0062	720	9	40	10.32	.....		.....
4	Series (one turn shorted out)	.0055	680	8	40	10.32	8.8		11.0%

Now let us assume we have 25 turns shorted out in one of the four shunt field coils in the motor shown in fig. 21. Our

characteristics will be as shown in Item 2, Table I, resulting in 4/10 of 1% loss in excitation of 1 coil and only $\frac{1}{8}$ of 1% loss in the total shunt field.

Let us assume we lose the excitation of only one turn out of nine turns per coil of one of the series field coils because of a short circuit. The effect shown in Item 4, Table I, is an 11.0% loss in excitation of one coil, or 2.8% for the entire field.

From these values we may conclude that a few turns loss in a shunt field coil is of little consequence but that we should have all series and interpole field coil turns active. Also note that coils with shorted turns and corresponding lowered resistance values have less I^2R losses, but the remaining coils in series have higher than normal I^2R or heat losses. A defective field coil may then overheat and destroy the insulation of the other field coils connected in series with it.

Shunt Field Coil Tests.—These may be tested by one of several methods. The universal and most used is the voltage drop test. Several coils are connected in series and excited by a suitable D.C. voltage supply. Then the voltage across each coil is measured and checked with the value found when the applied D.C. voltage is divided by the number of coils in series. This voltage drop test is illustrated in fig. 21.

Some variations are usually found as noted in Table I, which are permissible. Shunt coils are necessarily wound of many turns of relatively small wire and some variations in voltage drop must be expected because of slight stretching of the wire, variations in insulated wire outer diameter and consequent variations in coil mean turn length. In the case of random wound coils, a few turns may be shorted together, lowering the voltage drop. Another shunt field test of equal value to the

voltage drop test is the resistance test. In this test the resistance of each coil is checked with a direct reading ohm-meter.

Shunt coil tests that are used in various coil manufacturing plants include coil turn counters, radio frequency turn testers and A.C. balance testers. These are specialized test instruments and the economic justification of their purchase by the average user of coils is questionable.

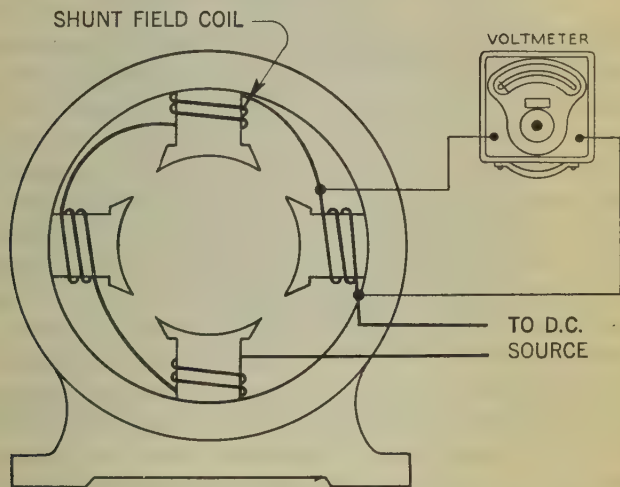


FIG. 21.—Voltage drop test of shunt field coils on a four-pole D.C. motor.

Coil Resistance Test.—For measuring the shunt, commutating and series field resistance, a special galvanometer measuring set is usually employed. A considerable amount of resistance of a series field may consist of contact resistance between the spools. After the heating test on a machine, the resistances of the various parts are measured and the rise in temperature calculated by the following method:

Let Rt_2 equal the hot resistance of the copper measured at temperature t_2 .

Let Rt_1 equal the cold resistance of the copper measured at temperature t_1 . Then:

$$t_2 = (234.5 + t_1) \left(\frac{Rt_2}{Rt_1} \right) - 234.5$$

Series and Commutating Field Coil Tests.—These have low resistances and require the use of Kelvin bridge type ohm-meters, similar to that shown in fig. 22, to accurately check their resistance values. Where this type instrument is not available, an alternating current growler test can be applied to the interpole and series field coil. This test is very satisfactory and is applied in the manner shown in fig. 23. Short circuited turns are indicated by increased primary current in the growler exciting coil and by heat rise of the coil under test. Never test shunt field coils on a growler of the type used for series field coil testing, as the induced voltages will puncture good turns and terminal insulation and the open circuit voltage at the shunt coil terminals may be from one to several thousand volts. The usual growler as used for series field coils will have a core cross-section of from 8 to 10 square inches and a magnetic flux density of from 60 to 100 kilo-lines per sq. in. The formula for induced transformer voltage is:

$$E = \frac{4.44BNfA}{10^8} \text{ volts}$$

Where B = maximum flux density in lines per square inch

N = Number of turns

f = Frequencies in cycles per second

A = cross section area in square inches

Accordingly, the induced voltage in a 3,000 turn shunt field coil on a 60 cycle series field coil growler with a core cross-section of nine square inches and a flux density of 60 kilo-lines will be 4,320 volts.

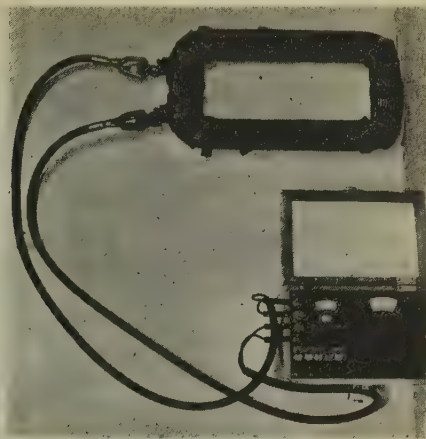


FIG. 22.—Use of Kelvin bridge in obtaining resistance of series field coils where values of resistance are exceedingly small ranging from 0.0001 to 1 ohm per coil.

The field coils of series wound motors may also be given a turn test without removing them from the motor frame by the use of a variable voltage transformer. Low A.C. voltage (10-100 volts) is applied across each coil and the A.C. current noted. A coil with shorted turns will be marked by a large percentage current increase.

An A.C. turn test must not be applied to the series and commutating field coils of a compound-wound motor while in the motor frame, as the induced voltages in the shunt coils may be of such magnitude as to destroy turn insulation in addition to being very dangerous.

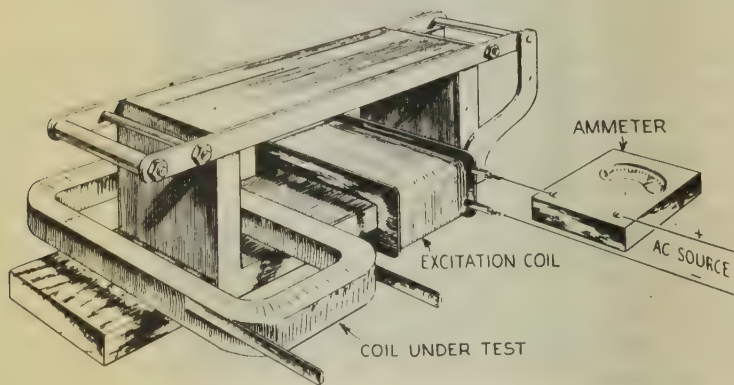


FIG. 23.—Simple alternating current growler as used in testing series field coils for turn-to-turn short circuits. The ammeter indicates the current in the exciting coil circuit.

Field Coil Polarity.—The polarity of the field coils in the motor frame should always be checked before installation of the armature and before complete re-assembly of the motor.

The polarity of the shunt coils may be checked by exciting the coils and observing whether the poles alternate in their attraction of a compass needle. If a compass is not available, an iron bar or nails may be placed so as to contact the lips of two adjacent pole pieces simultaneously. If the bar is attracted by both poles, the poles have correct polarity. If a pair of poles is found that tends to repel the bar, one of the poles has reversed or incorrect polarity.

The polarity of series field coils and commutating field coils may be checked with a compass and battery excitation on the coils. In the case of heavy strap-wound series and commutating field coils, a high amperage, low voltage, direct current may be circulated in these windings and the polarity checked either with a compass or by the iron bar method.

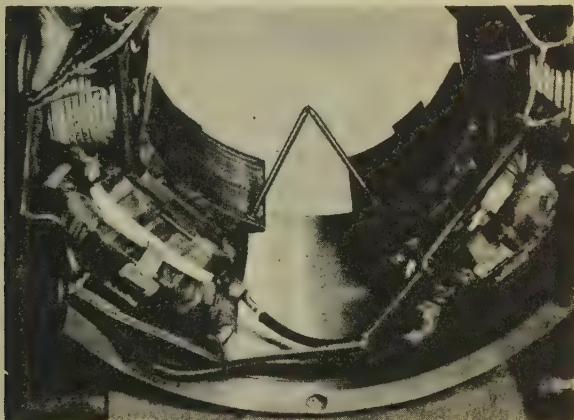


FIG. 24.—Illustrating polarity test on direct current motor. Here the polarity is being tested by placing two ordinary nails between adjacent field poles. The head of one nail should touch one pole tip, the head of the other, the other pole tip and the points should touch one another. When the nail points are attracted to one another, the polarity is correct. If an iron bar is used it should be long enough to reach from one pole to another.

Most compound-wound machines are accumulatively wound so that the series is the same as the shunt field polarity.

The commutating poles of a *motor* should have the same polarity as the main pole following it, with reference to the direction of rotation. The commutating poles of a *generator* should have the same polarity as the main pole ahead of it in the

direction of rotation. Another way of stating these rules is to say that the commutating field coil polarity "leads" the main field in a motor and "lags" the main field in a generator.

CHAPTER 26

Checking Winding Connections In A.C. Machines

Fundamental Rules for Checking Phase Relationship.—The direction of arrows in single, two- and three-phase windings should be carefully noted. Thus, in a single-phase winding *the arrows alternate*. In a two-phase winding *the arrows alternate in pairs*, that is, *two one way and two the other way*.

One of the fundamental considerations in connection with three-phase alternating current circuits is that, *if at a given instant the current in two of the lines flows in one direction, the current in the third line flows in the opposite direction*.

On this instantaneous basis the circuit may be treated for the purpose of analysis as though direct current were flowing. This principle may be applied to motors and generators. Accordingly a common method for checking the connections of three-phase machines, either on the actual winding or on the diagram of connections, is to consider the current as flowing into the winding by way of one lead and out by the other two, or vice versa.

Assume then in fig. 1 a three-phase star-connected concentric four-pole group winding, that the current is entering at *B* and *C*, circulating through the windings of these two phases, and then passing from the neutral or star point through the other phase to the terminal *A*.

When applying such a method, it is quite essential that the arrangement of the winding under consideration be known and, moreover, that a number of points be kept in mind in regard to the location of the leads, direction of polarity of the consecutive groups, and the order in which changes of polarity occur.

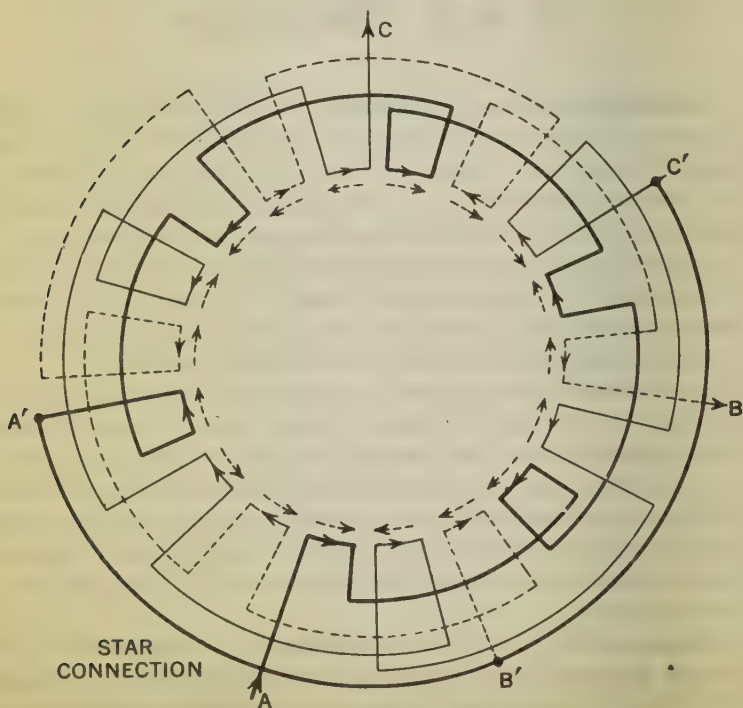


FIG. 1.—Four-pole, concentric group, three-phase *star* connected winding.

Thus, in figs. 2a, 2b and 2c, three methods of connection of a simple winding for a given voltage are shown, respectively, for a regular four-pole full pitch winding, a four-pole full pitch winding of the consequent pole type, and a two-pole winding of reduced pitch type obtained from the consequent pole winding by reversing the connections of alternate groups. The

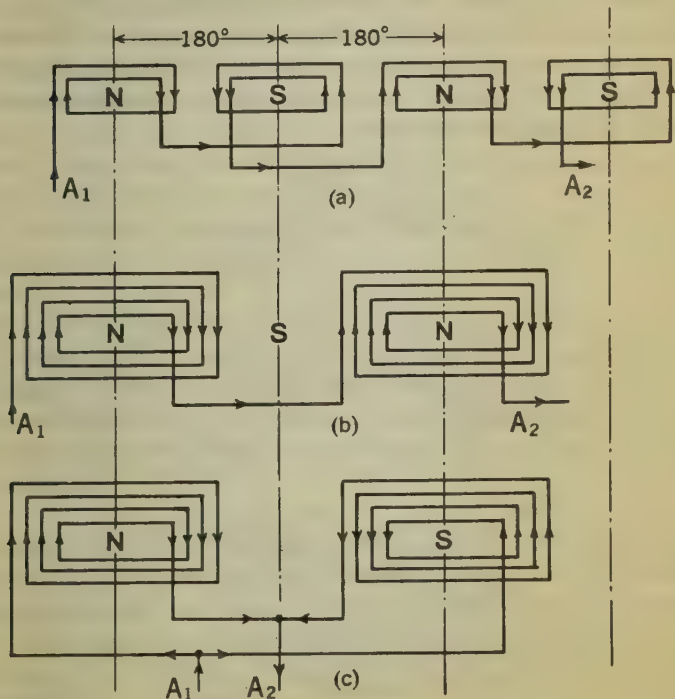


FIG. 2.—Characteristic methods of connection and arrangement of groups. *a*, shows a four-pole winding with alternately positive and negative groups; *b*, a four-pole winding of the consequent pole type; *c*, two-pole winding obtained from *b* by reconnecting the groups alternately positive and negative.

latter two combinations are sometimes used as a means of obtaining a two-speed motor with 2-to-1 speed ratio.

From fig. 2, in which a few of the possible arrangements are shown, it will be seen that it may be necessary to know in advance the type of winding in hand in order to check readily and intelligently the connections of the machine.

Generally the leads of the three phases are separated by a spacing of two poles (that is, an electrical angle of 120° apart) as shown in fig. 7, page 835. However, in fig. 8, page 836, the leads do not appear to be 120° apart, on account of the consequent pole arrangement.

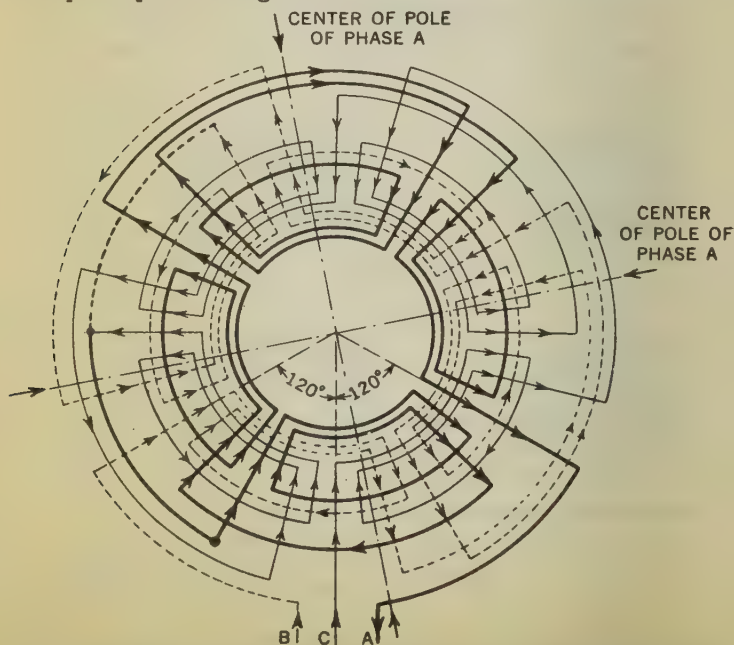


FIG. 3.—Six-pole, three-phase, *star connected* group winding with one phase purposely reversed.

In many cases, particularly on rotors, it is more convenient to tap off the leads at points farther apart than two groups; in such cases the method of checking referred to previously, in which the current is assumed as entering the winding at one lead and leaving it by way of the other two (or vice versa) may easily result in erroneous conclusions regarding the correctness of the connections.

This may be illustrated by reference to fig. 3, which shows a six-pole diagram with phase *B* reversed. Assuming that the current flows into lead *A*, and leaves by way of *B* and *C*, six poles per phase are actually obtained (the broken line arrows within the diagram are to be disregarded temporarily) yet with no proof that the three phases are connected in the right relation; for a further condition has to be fulfilled, namely, that the leads shall be 120 electrical degrees apart, or some multiple thereof.

This latter condition is not fulfilled in the case of phase *B*, this phase being reversed. In the case of a delta connection these rules cannot be applied directly in checking or laying out the connection of phases. Usually such a diagram is laid out as a star connection, the star then being connected into a delta, as shown in fig. 4.

Simple Universal Rule for Checking.—A method, such as the foregoing for checking windings is obviously not easily remembered and not always readily applied. This is particularly true when a winding has to be checked directly on the machine, as it is rather difficult to trace all of the connections throughout the winding.

A method which offers much better proof against mistakes, is simpler, and easier to remember, is briefly as follows: Assume that currents from a source of power flow into all three leads

of the star connection simultaneously, fig. 5, and meet at the star point; or, in the case of a delta winding, that the current in the delta connection flows completely around the delta in either direction; then the polarity of the consecutive groups will alternate regularly around the winding, fig. 6. The windings may thus be assumed as carrying direct current, the arrows indicating the direction of the current.

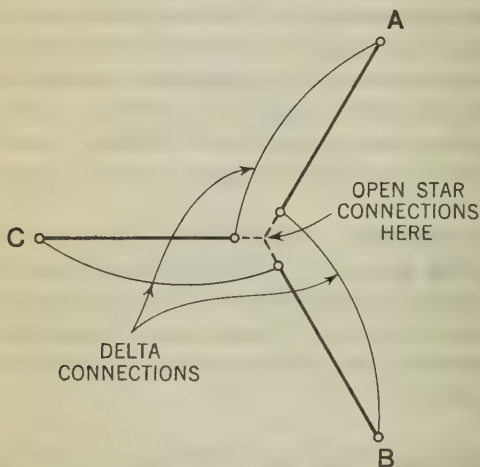


FIG. 4.—Showing method of changing *star* to *delta* connection.

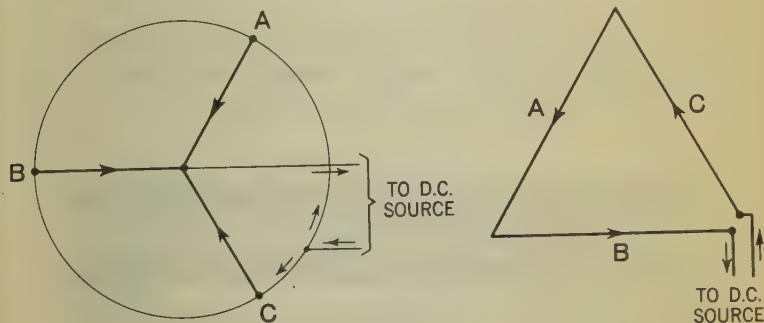
The actual instantaneous alternating current is of course not as indicated, but can be assumed so for purpose of checking. Thus, for a three-phase winding there would be three times as many poles as the rated number of poles of the machine.

With the present method of checking, the actual location of the leads and the phase relation of the respective groups does

not have to be considered; the fulfillment of the one condition of alternating polarity at regular intervals is a positive indication of correct connection of the groups of the winding.

For example, referring again to fig. 3, assume that the current is flowing from terminals *A*, *B* and *C* to the star connection; the polarity of the groups will now be as indicated by the broken line arrows within the diagram. The fact that phase *B* is reversed is now immediately evident.

The required phase relations in the winding would be obtained and the requirements of the present rule fulfilled if, for example, the terminal lead of phase *B* was connected at *A*, and the present terminal *B* was made the star connection.



FIGS. 5 and 6.—Showing method of checking a star and delta connected winding, respectively, with direct current.

If the winding of a completed stator such as indicated in fig. 1, for example, were being checked, the respective phases would be excited by low-voltage direct current applied across *ABC* connected together and the neutral point represented by *A*, *B*, *C* as shown in fig. 5, the polarity of the winding explored by means of a compass or magnetized needle held within the stator near the face of the iron.

Then there should be three times as many poles as the rated number of poles of the machine, reversing alternately and spaced equally provided the machine has a balanced winding. In the case of a delta-connected winding, it would be necessary simply to open the delta at any convenient point, such as at the point of connection of one of the terminals, and connect the two free ends to the source of power, as indicated in fig. 6.

CHAPTER 27

Winding of Fractional Horsepower Motors

Nameplate Data

The data supplied on *nameplates* is given as a guide not only for selection of the proper machine for a certain application, but also for re-winding and selection of proper control equipment, etc.

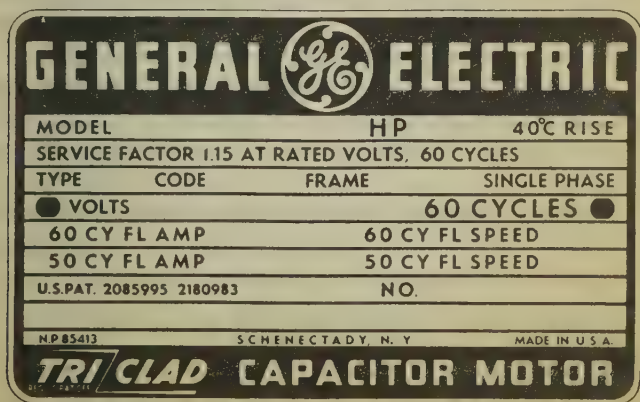


FIG. 1.—Showing name-plate of typical small power capacitor motor.

It is standard commercial practice to attach firmly to every machine, or other electrical apparatus before it leaves the factory, a brass information tag called *nameplate*. This usually gives the serial number by which the machine can be identified, tells the manufacturer's name, states whether the machine is a generator or motor, that it will deliver a specified number of horsepower (or fractions thereof), will run at a given speed, and will have a certain temperature rise when operated at stated frequency and voltage.

In addition, the nameplate supplies information as to whether the machine is to be employed on alternating or direct current; if alternating, for what frequency and how many phases; at what voltage; the maximum current for continuous operation, winding connections, torques, etc.

On some 60-cycle standard motors, 50 cycles is mentioned, and a 50-cycle current is given which implies that the motor may be operated on 50-cycle lines. A service factor is also given which allows the motor to be overloaded a slight amount.

Some of the foregoing items may be omitted on certain machines, but most of them are essential. Any person who wishes to become familiar with electrical machinery should form the habit of examining the nameplate of every machine which he is required to handle and note the difference in size, construction and use.

The *National Electrical Manufacturers Association* (NEMA) requires that the following minimum amount of information shall be given on all motor and generator nameplates:

1. Manufacturer's type and frame designation.
2. Horsepower output.
3. Time rating.
4. Temperature rise.
5. *R.p.m.* at full load.

6. Frequency.
7. Number of phases.
8. Voltage.
9. Full-load amperes.
10. Code ($\frac{1}{2}$ h.p. and larger).*

The foregoing terms are defined as follows:

Horsepower Output.—The horsepower number given on the nameplate is the *rated horsepower*, that is, the amount of horsepower developed when the motor is connected to a circuit having the same voltage, frequency and number of phases as that given on the motor nameplate.

Time Rating.—While some motors will develop their rated horsepower output *continuously*, others are designed for application on *intermittent service* and are rated to develop their horsepower for a limited period only. An example of the former are certain types of fan motors, while a household type of refrigeration motor, may be classified as for intermittent service.

By continuous duty is meant that requirement of service which demands operation at a substantially constant load for an indefinitely long time, without exceeding a given temperature rise. By intermittent duty is meant that requirement of service which demands operation for alternate intervals of time, at various conditions of load, without exceeding a given temperature rise.

The continuous duty motor nameplate is usually marked *Cont.*, whereas the intermittent duty motor nameplate is usually marked for a definite time interval such as $\frac{1}{2}$ hour, etc.

*NOTE.—The nameplate of every alternating current motor, except polyphase wound-rotor rated $\frac{1}{2}$ h.p. and larger, shall be marked with a caption "Code" followed by a letter to show locked rotor *kva.* per h.p.

Temperature Rise.—Practically all open general purpose motors are rated at a temperature rise of 40°C . above the room temperature; based on a room temperature (ambient) not exceeding 40°C . provided that the following conditions are complied with:

1. That the supply voltage and frequency is the same as that specified on the motor nameplate.
2. That the motor load does not exceed the specified horsepower rating.
3. That the free air flow through the motor is not obstructed.
4. That the temperature rise be taken at the hottest accessible spot on the winding and measured by a thermometer.
5. That the motor be not subjected to unusual conditions as specified by the *National Electrical Manufacturer's Association*.
6. That the altitude of operation does not exceed 3,300 feet.

R.P.M.—The term *r.p.m.* means the *revolutions per minute* of the motor shaft. As given on the motor nameplate it indicates the speed at which the motor will run when properly connected and delivering its rated output. It should be noted that the foregoing motor speeds are approximate only, except in the case of synchronous motors.

Frequency.—This is given on the motor nameplate as *cycles*, meaning the number of “cycles per second” the impressed alternating current reverses itself. The usual A.C. circuits carry a current which passes through 60 complete cycles or alternations per second, although 50 cycle currents are supplied in certain locations. Thus the motor nameplate

most often carries the designation 60 cycles, or sometimes 60/50; meaning that the motor may be operated on either one of these two frequencies.

It should be noted, however, that the speed of any A.C. motor varies with the line frequency according to the well-known formula $r.p.m. = 120f/\text{No. of poles}$. Thus, if a 60-cycle, 8-pole induction motor, for example, is connected to a 50-cycle supply, its speed would not be 900 *r.p.m.*, but would only be $900 \times 50/60$ or 750 *r.p.m.* In actual practice the speeds would be somewhat less, depending upon the amount of slip of the motor.

Number of Phases.—The number of phases are given on the motor nameplate as: single-phase, two-phase, or three-phase, in the case of alternating current motors. By the term *single-phase*, *two-phase*, or *three-phase* is meant that the motor is wound and designed for operation on a single-, two- or three-phase supply system.

Voltage.—The voltage specified on a motor nameplate refers to the effective voltage on which the motor is designed to operate. On certain dual-voltage motors, two voltage figures are given such as 110/220 which means that the motor is designed for operation on either of the two voltages. It should be noted, however, that such a motor is accompanied by special instructions for proper winding connections for each specified voltage.

Amperes.—The amperage given on motor nameplates represent the approximate number of amperes drawn by the motor when operating at full load and at the frequency and voltage as specified on the motor nameplate.

Since the motor current is a function of voltage and load, dual-voltage motors usually have two values of nameplate amperes, where the lower amperage rating corresponds to the high voltage.

Multi-speed motors similarly have two or more current ratings, that is, one for each motor speed.

Type-Letter Designations.—Manufacturers of small power motors usually assign *code letters* to the various types of motors, that is, a certain type of split-phase induction motor may have code letters Type-KH, KS, FH, etc., to designate the electrical characteristics and winding arrangement of the motors.

Similarly, a certain capacitor induction motor may have the letters Type HC, KCP, KCJ, etc., assigned to it.

It should be observed that each manufacturer has its own code or designation of type-letters.

Classification and Terminal Markings

Motor Ratings.—When discussing motor ratings there are two terms generally used, namely: *fractional* rating and *integral* rating. By definition, a fractional horsepower motor is a motor built in a frame smaller than that having a continuous rating of one horsepower open type, at 1,700-1,800 *r.p.m.*

By integral rating is generally meant a motor having a continuous rating of one or more horsepower.

It should be carefully noted that the determining factors in the rating of a motor is its speed and type of frame. Thus, for example, a 1 *h.p.* 3,450 *r.p.m.* 60 cycle motor has a fractional rating, while a $\frac{3}{4}$ *h.p.* 1,140 *r.p.m.* has an integral rating.

The motor ratings as given in Table I and smaller are generally identified as fractional horsepower motors, while all larger motors have integral horsepower ratings.

TABLE I

<i>R.p.m.</i>	Open Motors Brake <i>h.p.</i> Rating	Enclosed Motors Brake <i>h.p.</i> Rating
3,450	1	$\frac{3}{4}$
1,725	$\frac{3}{4}$	$\frac{1}{2}$
1,140	$\frac{1}{2}$	$\frac{1}{3}$
865	$\frac{1}{3}$	$\frac{1}{4}$

The NEMA standards for small-power A.C. motors have horsepower and speed ratings as shown in Table II.

Single-Phase Motor Types.—The single-phase motor was one of the earliest designs of A.C. motors. It has been improved throughout the years from the original repulsion type into many improved types, such as the modern split phase motor and the capacitor type. Single-phase motors are not necessarily manufactured in fractional horsepower ratings only, but are generally found in ratings of up to 5 *h.p.*

Since the operation and construction principles of fractional horsepower motors have been fully treated in another chapter, it will not be necessary here to devote further space to this matter. For the sake of clearness it bears repeating that the principal classes of single-phase fractional horsepower motors, depending upon their method of construction and operation are:

1. Split-phase (A.C.).
2. Capacitor (A.C.).
3. Repulsion (A.C.).
4. Universal (A.C. and D.C.).
5. Shaded pole (A.C.).

TABLE II

Brake <i>h.p.</i> Rating	60 Cycle		25 Cycle	
	Syn- chronous <i>r.p.m.</i>	Approx. Full Load <i>r.p.m.</i>	Syn- chronous <i>r.p.m.</i>	Approx. Full Load <i>r.p.m.</i>
1	3,600	3,450	.....	.....
$\frac{3}{4}$	3,600	3,450		
	1,800	1,725	1,500	1,425
$\frac{1}{2}$	3,600	3,450		
	1,800	1,725	1,500	1,425
	1,200	1,140		
$\frac{1}{3}$	3,600	3,450		
	1,800	1,725	1,500	1,425
	1,200	1,140		
	900	850		
$\frac{1}{4}$	3,600	3,450		
	1,800	1,725	1,500	1,425
	1,200	1,140		
	900	850		
$\frac{1}{6}$	3,600	3,450		
	1,800	1,725	1,500	1,425
	1,200	1,140		
	900	850		
$\frac{1}{8}$	3,600	3,450		
	1,800	1,725	1,500	1,425
	1,200	1,140		
	900	850		
$\frac{1}{12}$	3,600	3,450		
	1,800	1,725	1,500	1,425
	1,200	1,140		
	900	850		
$\frac{1}{20}$	3,600	3,450		
	1,800	1,725	1,500	1,425
	1,200	1,140		
	900	850		

These general classifications may again be subdivided to include the various starting arrangements. The split-phase induction motor for example, may be of the resistance-start or the reactor-start type.

The capacitor motor may be of the capacitor-start or capacitor-run type, depending upon whether the capacitor is disconnected after starting or not.

Similarly the repulsion motor may be of the repulsion-induction or the repulsion-start-induction type.

The universal type of motor may be of the distributed field compensated or the concentrated-pole non-compensated type.

Shaded pole motors differ principally in the arrangement of the shading coils.

Terminal Markings.—The necessity for a uniform method of terminal markings of motors is of the utmost importance, since improper terminal markings may result in faulty connections of windings with accompanying damage to the motor or at best unsatisfactory performance.

The system of terminal markings of single-phase motors as given by NEMA are shown in figs. 2 to 25.

The markings of terminals for single-phase motors are based on the following principles:

1. Designate the running winding of a single-voltage single-phase motor by $T_1 T_4$ and the starting winding by $T_5 T_8$. This distinguishes it from a quarter-phase motor which uses odd subscript numbers in one-phase and even subscript numbers in the other phase.
2. The first principle permits a dual voltage motor to have markings which follow the general practice now used of connecting odd to odd and even to even for

parallel (low voltage) connection and connecting odd to even for series (high voltage) connection.

3. Always represent the rotor by a circle on schematic diagrams of single-phase motors, even though it has no external connections. This indicates definitely whether it has any connections (short circuits or external) and further distinguishes the diagram and markings from a quarter-phase schematic which never shows the rotor as a circle.

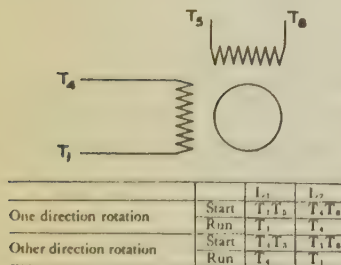


FIG. 2. --Split phase with automatic cutout reversible motor.

FIG. 3. --Split-phase with automatic cutout non reversible motor.

Single-Phase, Dual-Voltage Motors. -- Regardless of the type of single-phase motor, when a series or parallel connection of any winding is necessary, proceed as follows: Divide single winding into two halves and assign $T_1 T_2$ to one-half and $T_3 T_4$ to the other half of running-winding. Assign $T_5 T_6$ to one-half and $T_7 T_8$ to the other half of starting- or reversing-winding. This is shown diagrammatically in fig. 17.

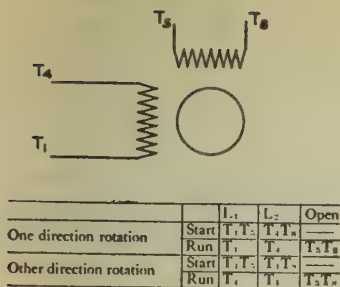


FIG. 4.—Split-phase manual cutout reversible motor.

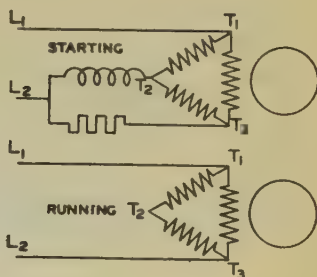


FIG. 5.—Induction motor with starting box non-reversible.

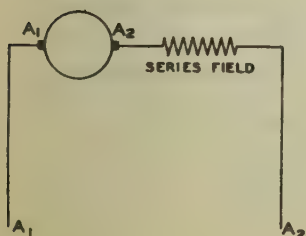
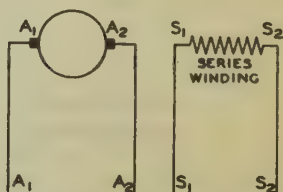


FIG. 6.—Series universal non-reversing motor not compensated.



	L ₁	L ₂	Tie Together
One direction rotation	A ₁	S ₂	A ₂ , S ₁
Other direction rotation	A ₁	S ₁	A ₂ , S ₂

FIG. 7.—Series universal motor not compensated.

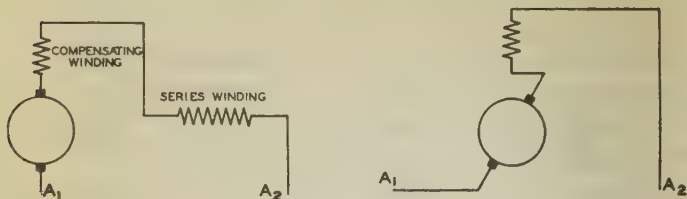


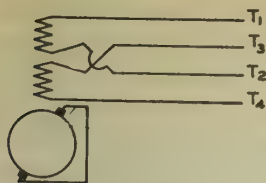
FIG. 8.—Series motor conductively compensated separate stator windings. Motor may be reversed by reversing the series field only.

FIG. 9.—Series motor conductively compensated common stator windings. Motor may be reversed by shifting brushes as per manufacturer's instructions.

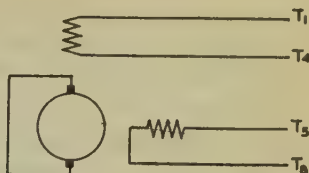


FIG. 10.—Series motor inductively compensated separate stator windings. Motor may be reversed by reversing the series field only.

FIG. 11.—Diagram representing: (1) Repulsion motor, single voltage not compensated. (2) Repulsion start, induction-run motor, single voltage not compensated. Motor may be reversed by reversing the series field only.



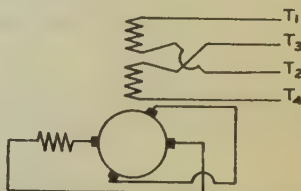
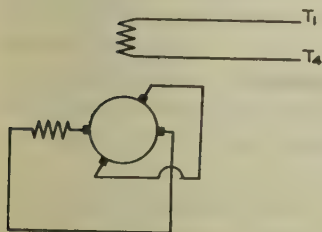
	L ₁	L ₂	Tie Together
Low Voltage	T ₁ T ₃	T ₂ T ₄	—
High Voltage	T ₁	T ₄	T ₂ T ₃



	L ₁	L ₂	Tie Together
One direction rotation	T ₁	T ₄	T ₅ T ₆
Other direction rotation	T ₁	T ₅	T ₄ T ₆

FIG. 12.—Diagram representing: (1) Repulsion motor, double voltage not compensated. (2) Repulsion-start induction-run motor, double voltage not compensated. Motor may be reversed by shifting brushes as per manufacturer's instructions.

FIG. 13.—Diagram representing: (1) Repulsion motor, single voltage, reversible. (2) Repulsion start induction-run motor, single voltage, reversible.

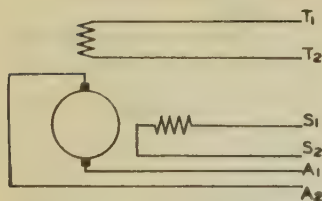


	L ₁	L ₂	Tie Together
Low Voltage	T ₁ T ₃	T ₂ T ₄	—
High Voltage	T ₁	T ₄	T ₂ T ₃

FIG. 14.—Repulsion motor single-voltage inductively compensated. Motor may be reversed by shifting brushes as per manufacturer's instructions.

FIG. 15.—Repulsion motor, double voltage inductively compensated. Motor may be reversed by shifting brushes as per manufacturer's instructions.

9i2 Winding of Fractional Horsepower Motors



	L_1	L_2	Tie Together
One direction rotation	A_1	S_1	S_2 to T_1 & A_2 to T_2
Other direction rotation	A_1	S_2	S_1 to T_1 & A_2 to T_2

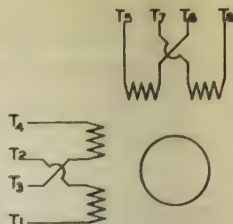


FIG. 16.—Series motor conductively compensated reversible, separate stator windings.

FIG. 17.—Diagram showing winding arrangement and terminal markings of single-phase dual voltage motors.

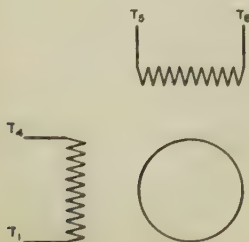


FIG. 18.—Diagram representing: (1) Capacitor start, capacitor run motors. (2) Capacitor start, induction run motors. To be connected to capacitor in accordance with manufacturer's diagram.

Capacitor Motors.—Where auxiliary devices (capacitors, transformers, contactors, relays or centrifugal switches) are included in or on the motor frame and permanently wired to the motor or where several auxiliary devices are assembled in a separate enclosure and are permanently wired together therein, terminal markings need be used only on leads coming out of the motor or from the separate enclosure. The terminal markings to be used for these leads shall be determined from the following standards.

Subscript Numerals for Capacitors and Transformers.—Subscript numbers of the letters *J*, *H* and *X* shall be the same as the subscript number of the terminal marking *T* of the motor lead to which they connect when the motor is connected for standard rotation.

If the lead from a capacitor or transformer connects to a junction of two motor leads on a single voltage motor, the subscript number of *H*, *J* or *X* will be the lower of the numbers used for the interconnected motor leads when connected for standard rotation.

On dual voltage motors, the high voltage connection shall determine the subscript number of *H*, *J* or *X*, even though the low voltage connection is to be used.

Subscript Numerals for Relays, Contactors and Centrifugal Switches.—External leads from the contacts of relays, contactors or centrifugal switches, when connected to motor, transformer or capacitor, shall bear the same terminal marking and subscript number as those used on the device to which each contact is connected when the motor is connected for standard rotation (this is standard control practice).

The coil terminals of relays or contactors shall bear the

terminal marking and subscript number of the lead of the devices to which they connect, the lowest subscript being used when connected to a junction of two or more leads.

Interconnections solely between relays, contactors and centrifugal switches, either contacts or coils, shall bear a common numeral at each end, but no letter, and the numeral must be higher than the highest subscript numeral used on the motor, capacitor or transformer.

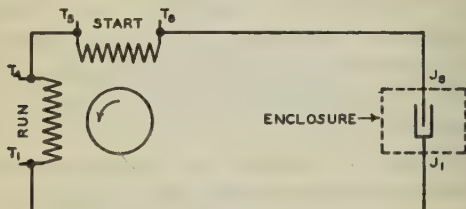


FIG. 19.—Low torque motor capacitor only.

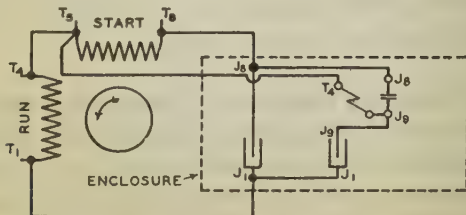


FIG. 20.—High torque capacitor motor with capacitor and contactors.

Subscript Numerals for Interconnections between Auxiliary Devices.—On an interconnection between a capacitor and a transformer or between either of these devices and a relay, contactor or centrifugal switch where there is no connection to a motor lead, a common subscript numeral shall be assigned to the letters *J*, *H* or *X*, used on the interconnected terminals which numeral must be higher than any subscript numeral used on any terminal marking of the motor leads. The relay, contactor or centrifugal switch terminal will take the same letter and subscript as the transformer or capacitor to which it connects.

Terminal Markings for the Starting and Running Windings. The terminals for starting and running windings for capacitor motors shall be marked in accordance with the principles established for single-phase motors.

Connections and Terminal Markings for Capacitor Motors.—The connections and terminal markings for most capacitor motors now in use are as illustrated in diagrams figs. 18 to 25.

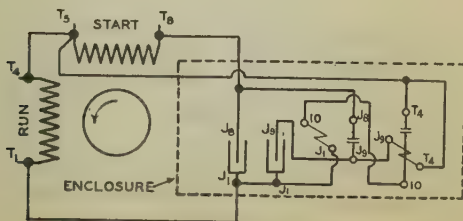


FIG. 21.—High torque, capacitor motor with relay and contactor.

On some types of motors, however, particularly those of foreign manufacture, and also those of older domestic types, the terminal markings may differ from that shown in the illustrations, and it is recommended that if the terminal markings are undistinguishable or missing, that each lead be properly tested and identified prior to putting the motor in service.

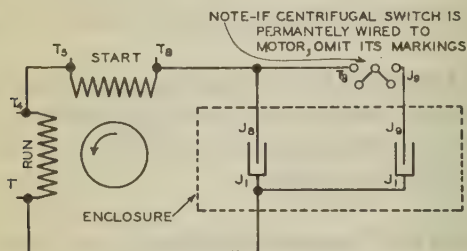


FIG. 22.—High torque, capacitor motor and centrifugal switch.

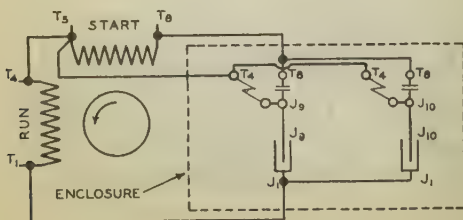


FIG. 23.—High torque, capacitor start, capacitor run motor, with two contactors.

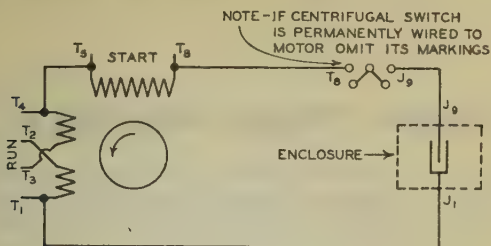


FIG. 24.—Capacitor start, induction run, dual voltage motor.

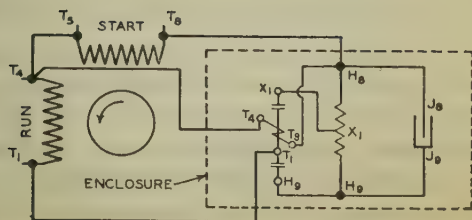


FIG. 25.—Capacitor start and run motor, with double throw contactor, transformer and capacitor.

Single Phase Windings

Winding Types Used.—Stator windings of single-phase induction motors may be divided into two general classes, namely:

1. Single winding.
2. Double- or split-phase winding.

The distributed type single-phase winding is generally used on such common types as repulsion and repulsion-induction motors, whereas the concentrated single-phase winding is commonly used on shaded pole motors.

Motors for operation on single-phase A.C. circuits may be divided into two general classes, namely:

1. Those having split-phase primaries and squirrel-cage rotors.
2. Those having single-phase primaries and wound rotors.

The primary winding of the split-phase motor consists of a main or running-winding and a starting-winding, which is generally displaced 90 electrical degrees from the main winding. The starting-winding is usually cut out of the circuit by a centrifugally-operated switch before normal speed is reached.

The primary winding of the single-phase wound-rotor motor is similar to the main or running-winding of the split-phase motor. A starting-winding is not required because such motors are inherently self-starting. Such motors are usually designated as repulsion, repulsion-induction or repulsion-start induction motors.

There are several methods of winding the primaries of small single-phase motors, which are in common use today. They are:

1. Skein winding.
2. Mold winding.
3. Hand winding.

Skein Winding.—In skein windings, a skein of wires is looped a number of times through the slots to form one pole. Thus, the total number of turns per pole is a multiple of the number of turns in the skein.

The multiple depends upon the number of times the skein is looped through the slots and the number of slots per pole. When rewinding a skein-wound motor the number of times the skein is looped through each slot should be noted, the length of the skein measured and the turns counted.

In case the skein length is not obtainable directly from the old winding, it may be calculated from the dimensions of the primary core by considering the mean diameter D of the winding to be the distance from center to center of diametrically opposite slots, as shown in fig. 29. Using this value of D the pole pitch at the slot centers is calculated from the formula:

$$\text{Pole pitch} = \frac{\pi D}{\text{Poles}}$$

This distance is then laid out as a development; the slot centers are indicated by dots on this line and the probable mean line of each loop is drawn, as in fig. 31, assuming the probable coil extension E , fig. 29.

The lengths L_1 , L_2 , L_3 and L_4 are measured and each length is multiplied by the number of times the skein is looped through the slots for that length. Then these products are added

together, and the sum is multiplied by two to include the extensions on the other side of the core. To this total is added the product of core width by the number of times the skein bundle crosses the core. This gives the total skein perimeter.

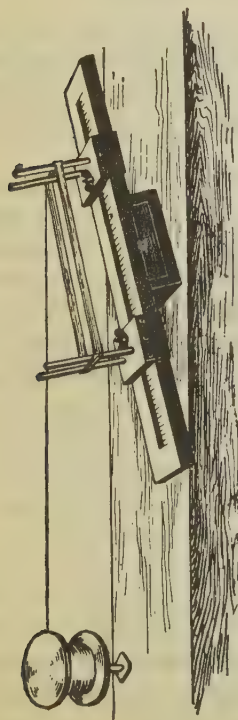


FIG. 26.—Adjustable shuttle or skein winder showing operation of winding a skein corresponding to fig. 27.

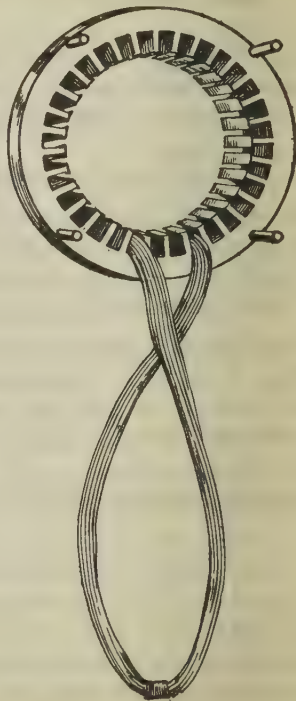


FIG. 27.—Skein placed in slots and half twist taken ready for the second operation.

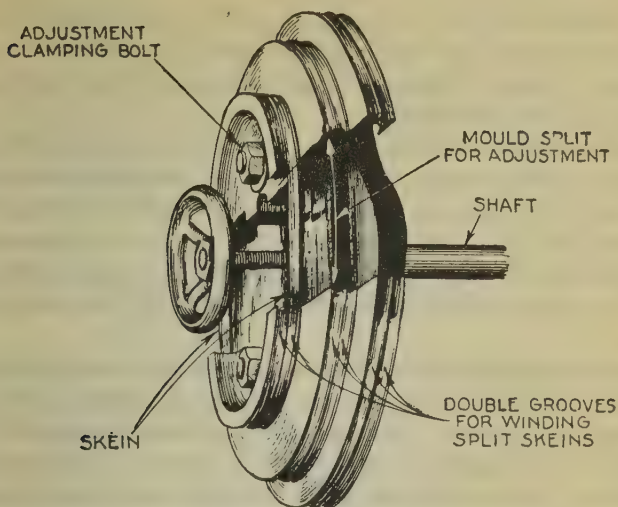
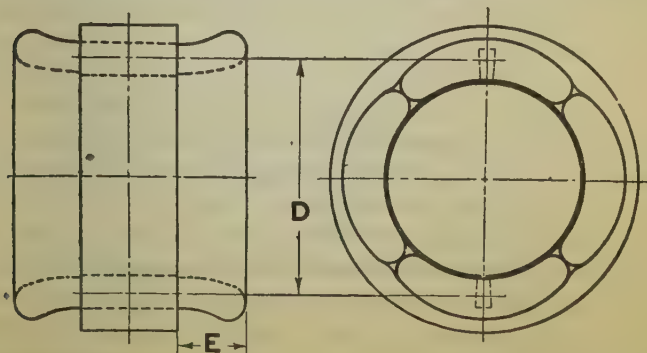


FIG. 28.—Winding head for winding skeins. The double grooving permits winding two skeins of the same size or one split skein. When the skein is over $\frac{1}{2}$ in. square and of wire larger than No. 19, it should be wound in two sections. Note that the winding mould is split through the center so as to be adjustable for different sizes of skeins.



Figs. 29 and 30.—Shape of connecting coils for single-phase motors.

A trial skein with the required number of turns should first be made and wound, and the length corrected, if necessary, for the remaining skeins. After a little experience, the corrections will usually be unnecessary.

Another method of determining the skein length or perimeter is by trial with a single wire. This wire should be laid in the slots just as the skein of wire would be inserted, making proper allowance for the bundle of wires the single wire represents. Then this wire is removed and measured; one skein is wound for trial, and correction is made, if necessary, for the succeeding skeins.

The distribution of the windings in the slots varies with the design of the motor and depends upon the number of slots and the number of poles. The distribution most commonly used in a 36-slot, four-pole motor is shown in Table I. The numbers in the slots indicate the number of times the loop passes through each slot. Table II shows another distribution for the same number of slots and poles, which is less common because the starting winding is too concentrated with this distribution.

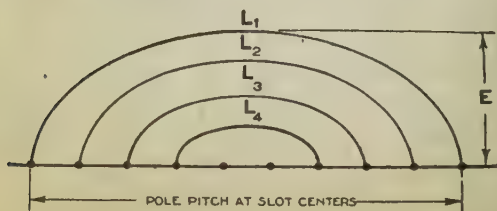


FIG. 31.—Diagram illustrating method of determining length of loops.

TABLE I

Winding Table for a 36-Slot Motor

SLOT NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	
MAIN WINDING	1 1	2	2	1			1	2	2	1 1	2	2	1			1	2	2	1 1	2	2	1				1	2	2	1 1	2	2	1			1	2	2
STARTING WINDING				1	1	1	1							1	1	1	1							1	1	1	1					1	1	1	1		

TABLE II

Winding Table for a 36-Slot Motor

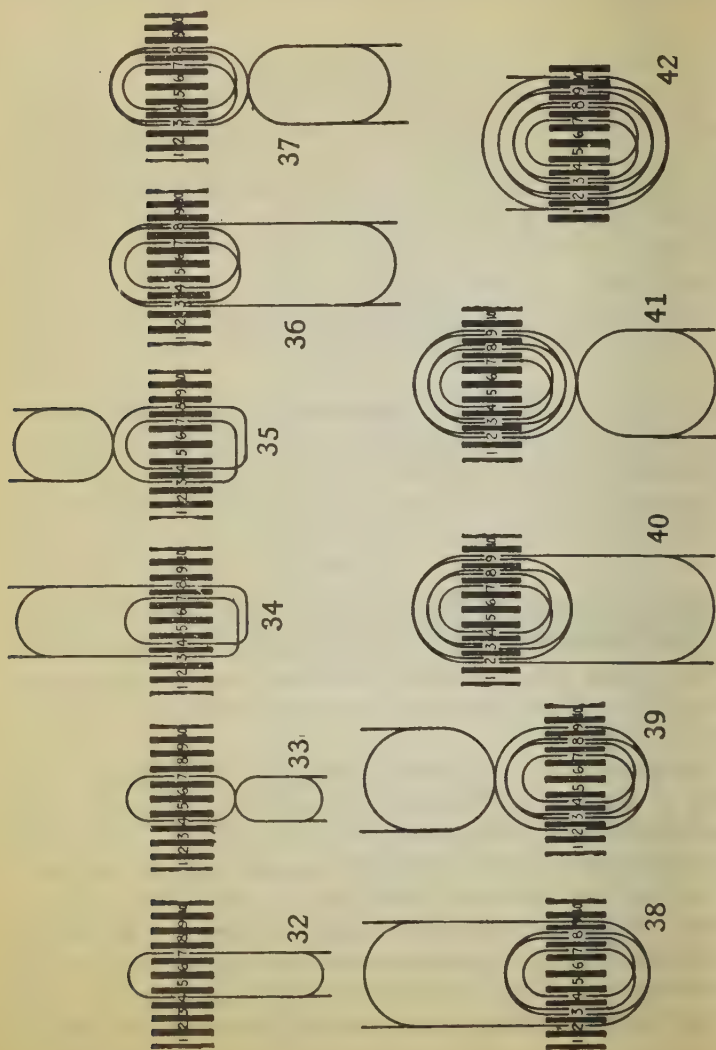
(with less common distribution)

SLOT NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
MAIN WINDING	1	1	1				1	1	1	1	1	1				1	1	1	1	1	1				1	1	1	1	1	1				1	1	1
STARTING WINDING					2	1 1	2						2	1 1	2								2	1 1	2						2	1 1	2			

Winding Procedure.—After the skein length and distribution have been determined and the slots insulated, the procedure in winding a single pole of a four-pole, 36-slot primary is as shown in figs. 32 to 42 for the main winding distribution given in Table I.

A developed view of a small portion of the primary core, looking at the teeth, with the first operation of putting the skein in slots 4 and 7 completed, is shown in fig. 32. The short end of the skein should be firmly pressed against the core. The leads of the coil should be on the long end of the skein.

A half twist is next made in the skein, as shown in fig. 33 and the long end of the loop is then passed through the core and the sides are threaded into slots 3 and 8, as shown in fig. 34. The winding should be pressed firmly against the side of the core.



Figs. 32 to 42.—Detail of slots and skein showing progressively the method of winding a skein with distribution as specified in Table I.

The half twist is repeated, as shown in fig. 35, but the twist should be made in the opposite direction to the first twist.

Throughout the winding the half twists should be alternated in direction so as not to snarl the winding on the last loop. The loop is then laid back in slots 3 and 8 for the second time, as in fig. 36. The half twist shown in fig. 37 is then made and the loop laid in slots 2 and 9, as in fig. 38.

Again a half twist is given, fig. 39, and the skein is laid back in slots 2 and 9 for the second time, as shown in fig. 40. Another half twist, shown in fig. 41, is made and the skein is threaded into slots 1 and 10, fig. 42, thus completing the winding of one pole.

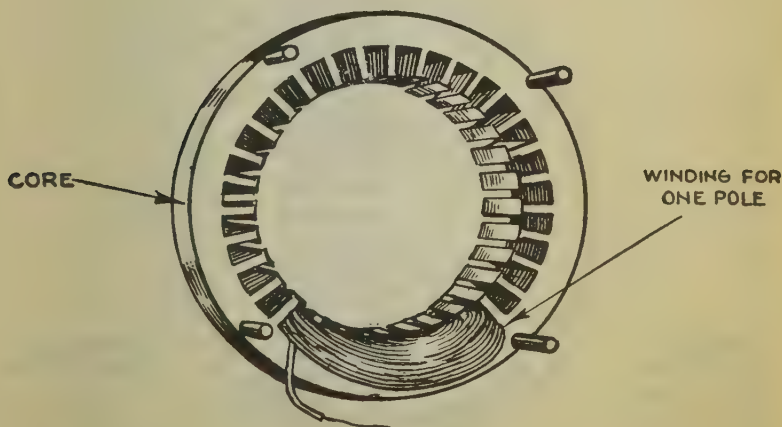


FIG. 43.—Field core showing one pole completely wound corresponding to fig: 42.

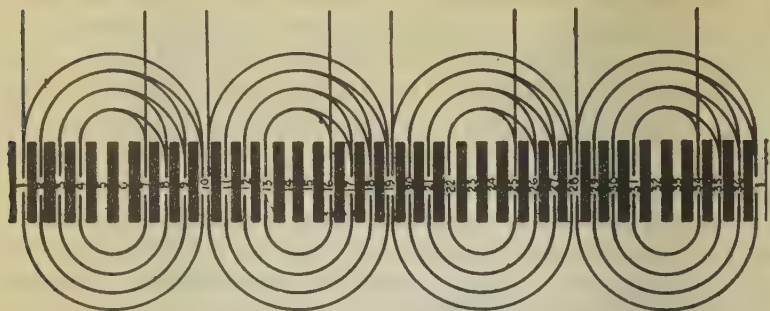
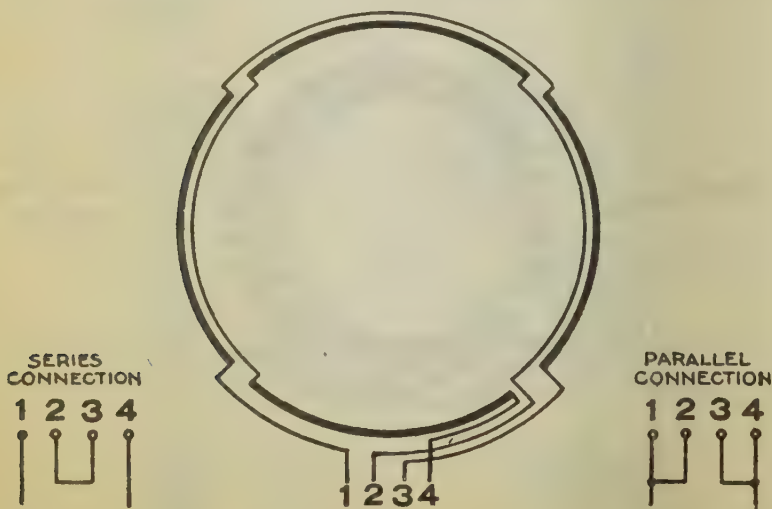


FIG. 44.—Diagram showing completed main field skein winding with each pole wound as shown progressively in figs. 32 to 42.



FIGS. 45 to 47.—Diagrams showing connections for winding in fig. 54.

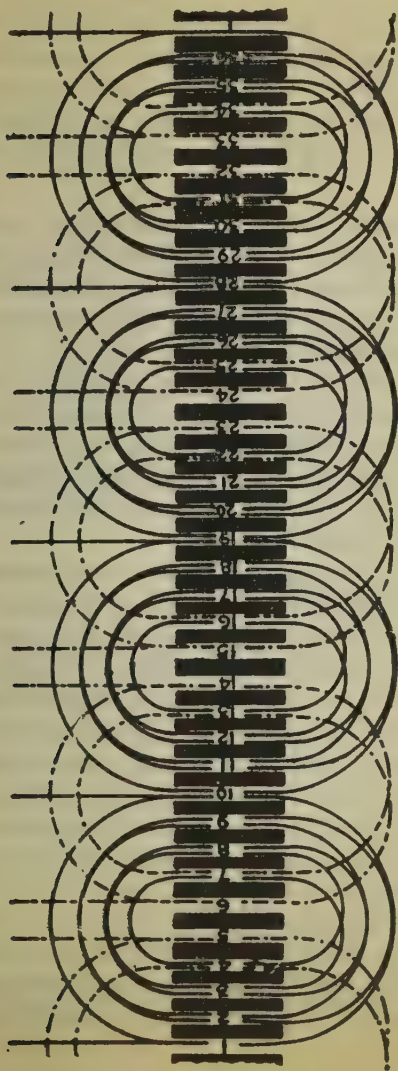


FIG. 48.—Diagram showing completed main and starting windings.

It is very important that the direction of the half twists be alternated to obtain a smooth winding and to avoid difficulty on the last part of the loop. The winding of the second and remaining poles is performed exactly the same as that of the first. The completed winding for a four-pole, 36-slot motor is shown in fig. 54.

For repulsion-induction and repulsion-starting, induction-running motors, the primary winding is complete as shown in fig. 54, and the coils are connected together as shown in fig. 49. Four leads are usually brought out so that these motors may be connected externally for either 220 or 110 volts.

For single-phase motors with squirrel-cage rotors, an additional winding is required on the primary to start the motor. This winding is called the starting-winding and is connected across the line until approximately two-thirds synchronous speed is reached, when its circuit is automatically opened by a centrifugally-operated switch.

This starting-winding is displaced 90 electrical degrees from the main winding, or in other words, the pole centers of the starting-winding are located midway between the pole centers of the main winding. Its distribution and the length of the skein must be determined as explained for the main winding.

The starting winding is essentially a resistance winding. As it is important that its resistance in the rewound motor be the same as it was originally, the length of the skein should be carefully determined. The distribution of both the main and starting-winding and the number of times the skein bundle passes through each slot are shown in fig. 48.

The main and starting winding coils should be connected together as shown in fig. 49 or fig. 50. The particular diagram to be used depends upon whether the winding is to be connected in series or in series-parallel for the circuit on which the motor is to operate.

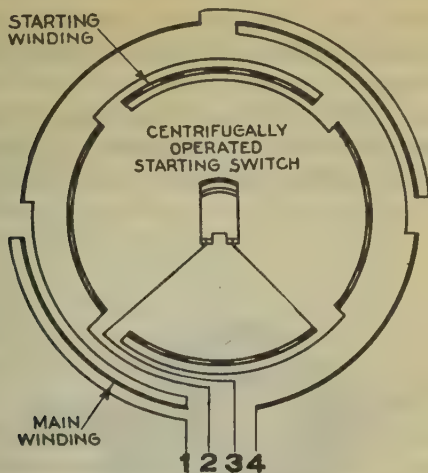


FIG. 49.—Diagram showing series connections of four pole motor. Clockwise rotation: Connect 1 and 2 to one line; connect 3 and 4 to other line. Counterclockwise rotation: Connect 1 and 3 to one line; connect 2 and 4 to other line.

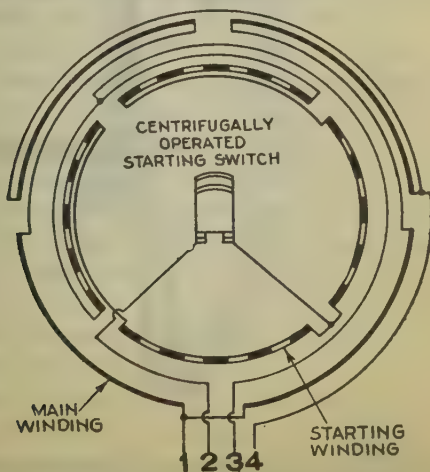


FIG. 50.—Diagram showing connections of a four pole, two path motor. Clockwise rotation: Connect 1 and 2 to one line; connect 3 and 4 to other line. Counterclockwise rotation: Connect 1 and 3 to one line; connect 2 and 4 to other line.

It will be noted in fig. 48 that the poles lap in slots 1, 10, 19 and 28 for the main winding. This is not essential but depends upon circumstances.

The winding in the particular motor selected for the example could have been distributed as indicated in Table II. In that case the starting-winding would not have advantageous dis-

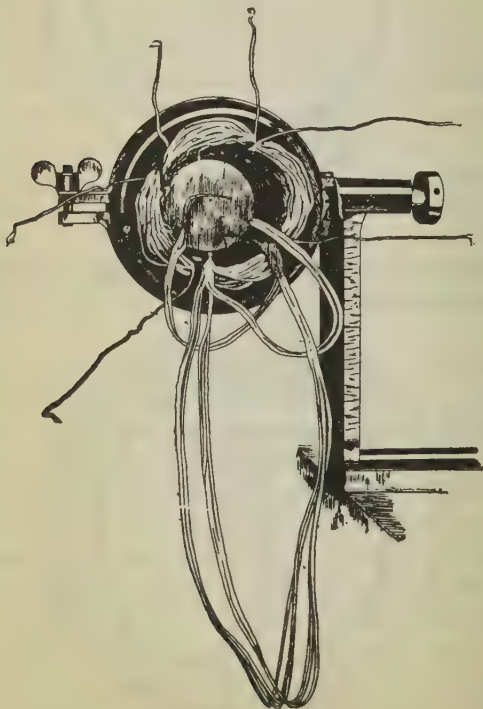


FIG. 51.—Method of winding split skein in the slots. First or bottom section is shown twisted and being wound into the slots first to reduce the piling up of the ends.

tribution as in Table I, and a smaller size of wire would probably be required for the main winding because the number of wires per slot would be higher for the same effective number of turns and, consequently, the copper loss would be higher.

Under some conditions, however, and with other pole and slot combinations, it is often advantageous to distribute the winding so that adjacent main poles do not lap.

Mold and Hand Winding.—The mold winding method is sometimes employed in winding small motors of the induction type. It takes its name from the fact that the pole coils are first wound on a mold, and then placed in the slots.

In most cases one pole set of coils is wound together so that individual coils do not have to be connected together after being placed in the slots. As far as the final results are concerned, the mold type of winding has the same general appearance as the hand type.

Any mold-wound small motor can be hand wound, that is, one wire at a time wound in by hand, when it is repaired. The winding diagram of both the mold-wound and hand-wound motors is the same and is shown in fig. 54 for the main winding.

The starting windings of motors with either mold-wound or hand-wound main windings are generally skein wound, although they are not hand wound because the resistance of the starting-winding is very important, and in the case of a hand winding, would vary too much.

In case the starting-winding is skein wound, the procedure is the same as previously described.

When the starting-winding is mold wound, and no mold is available for rewinding, it is necessary to measure the entire length of the starting-winding coil of one pole of the motor to be rewound and to wind that same amount of wire into the slots.

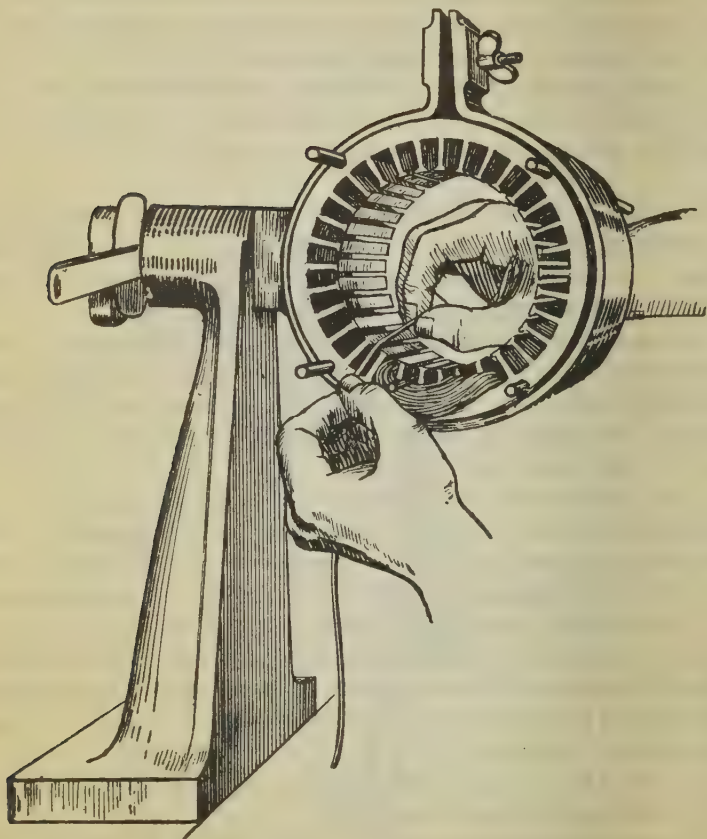


FIG. 52.—Method of hand winding showing how a loop of wire is slipped through the opening and into the slot. A skein winding may be put on in the same manner, but requires more experience.



FIG. 53.—Placement of rods in slots which are to be left partially vacant when putting on the main winding. The wire is wound around underneath these rods which hold the coils down and reserve room for the starting winding.

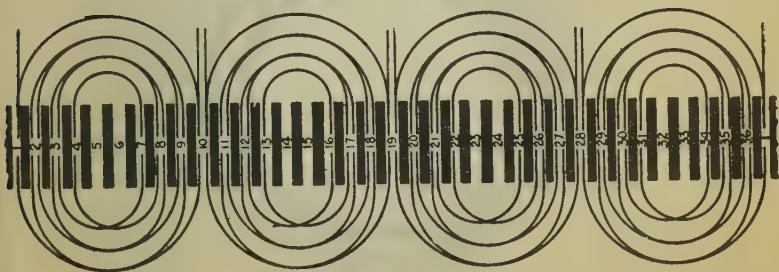


FIG. 54.—Diagram of main winding for mould or hand winding.

The split-phase cage-wound and single-phase wound-rotor motors most commonly encountered have two, four or six poles. The four-pole, 36-slot winding and connecting diagrams have been given in connection with the description of the method of winding. Two- and six-pole winding distributions and connections are shown in figs. 55 to 60.

TABLE III

Winding Table for 2-Pole 24-Slot Motor

SLOT NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
MAIN WINDING	1 1	2	2	2	1				1	2	2	2	1 1	2	2	2	1				1	2	2	2
STARTING WINDING			1	2	2	2	1 1	2	2	2	1				1	2	2	2	1 1	2	2	2	1	

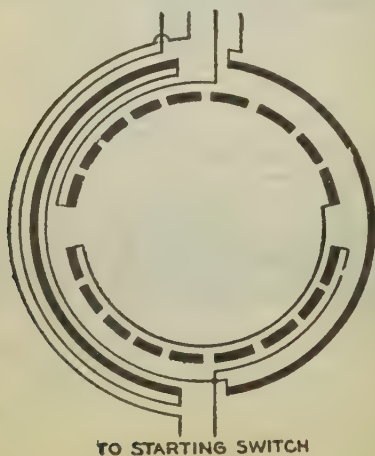


FIG. 55.—Diagram showing series connections for a two pole motor.

TABLE IV
Winding Table for 6-Pole 36-Slot Motor

SLOT NO.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
MAIN WINDING	1	1	2	1	1	2	1	1	2	1	1	2	1	1	2	1	1	2	1	1	2	1	1	2	1	1	2	1	1	2	1	1	2	1	1	2
STARTING WINDING			2	1	1	2			2	1	1	2			2	1	1	2			2	1	1	2			2	1	1	2			2	1	1	2

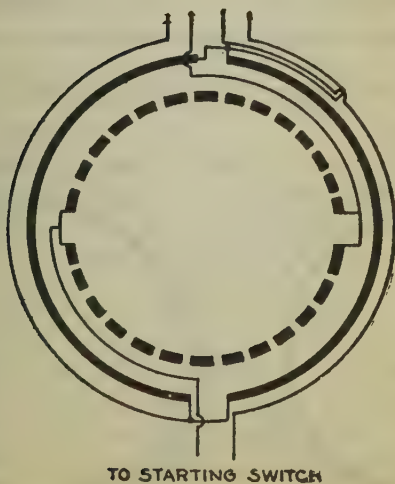


FIG. 56.—Diagram showing connections for a two pole two path motor.

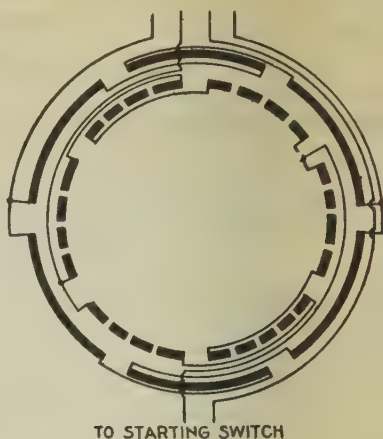
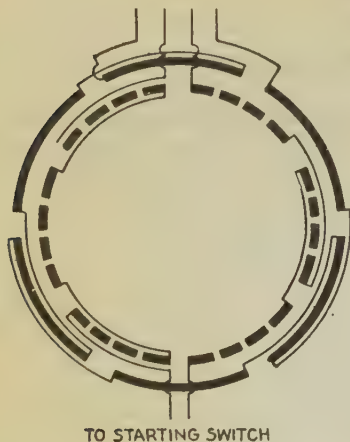


FIG. 57.—Diagram showing series connections for a six pole motor.

FIG. 58.—Diagram showing connections for a six pole two path motor.

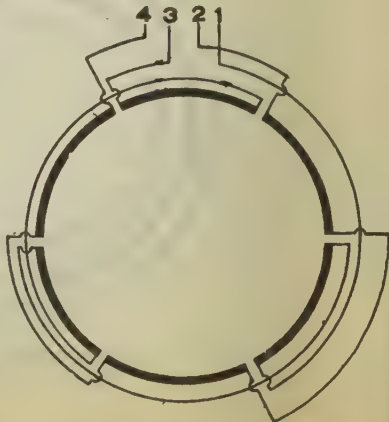
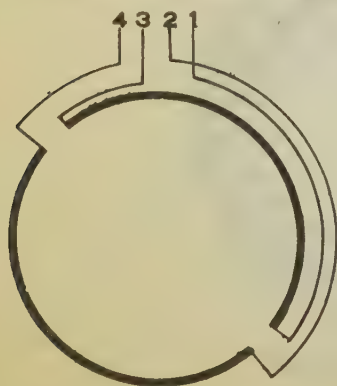


FIG. 59.—Diagram showing connections for a two pole repulsion-induction motor.

FIG. 60.—Diagram showing connections for a six pole repulsion-induction motor.

CHAPTER 28

Rewinding of A.C. and D.C. Machines

Rewinding Direct Current Armatures

General.—Rewinding of direct current armatures requires a thorough knowledge of the operation to be performed, expert workmanship and a certain amount of special equipment. Unless complete facilities and workmen experienced in this kind of work are available, it is generally advisable to return the armature to the factory when rewinding is necessary.

Winding Data Required.—Prior to dismantling the armature, it is necessary to have all the winding data irrespective of whether the armature is new or old and no matter what the type may be. The following is a list of the data required:

Maker's Name—— Class—— Type—— Spec. No.——
Voltage—— Capacity—— D.C. or A.C.—— Phase
cycles—— Amperes—— Speed—— Armature or stator——
Number of turns per coil—— Size and covering of wire——
Number of coils per bundle or slot——

Number of teeth the coils go around (usually expressed as "8 teeth"), or

Number of the slots the coils go in (usually counted as one more than the enclosed number of teeth as "1 and 9")

Lead between the armature winding and the commutator
Number of poles—— Insulation of core (if complex)
The above data applies to practically all types of armatures.

If the armature is form wound or multipolar the following should also be obtained:

Save a sample coil
Insulation on the coil (if formed)
Number of commutator bars
Span of the leads

Sundry data as to whether multiplex; connection of equalizer rings if any, and such unusual items.

Dismantling the Armature.—When an armature is brought into the shop to be rewound, it must first be stripped of the old winding and re-insulated throughout. In reinsulating, the first operation is to remove the banding wires, being careful not to mash the armature teeth with the chisel.

The coil ends of the armature are secured to the commutator necks or risers by soldering or brazing. Most machines of older manufacture have soldered connections with the coil ends fitting in a slot in the necks.

Many machines built during recent years, however, have a silver brazed butt joint between coil end and neck. The former type of joint may easily be separated by means of a soldering iron, but the latter will usually require the use of a gas flame or torch, because of the higher melting temperature of the bonding material.

NOTE.—A "coil" may be defined as the wire or turns from one commutator bar to the bar connected to its other end.

NOTE.—A "bundle" is a number of single coils grouped together in a slot.



FIG. 1.—View of typical motor repair shop. A well planned motor maintenance program calls for overhauling of motors at regular intervals. (Courtesy General Electric Co.)



Fig. 2.—Illustrating winding of armature of a 250-h.p. 400/1,200 r.p.m., 230-volt D.C. motor with "Frog-leg" type coils.
(Courtesy Allis Chalmers Mfg. Co.)

In doing this work great care must be exercised to prevent the solder from getting into the commutator and the joint should be cleaned at the same time to be in the right condition for reassembly. If only part of the coils are to be replaced, the rest of the coils must be protected by means of asbestos pads to prevent injury to insulation, particularly if it is necessary to use a flame or torch for separation.

If the armature is to be completely rewound great care must also be used in placing the coil sides in the slot having the correct slot pitch for the particular machine and similarly that the coil ends are started in the commutator necks having the proper spread or pitch.



FIG. 3.—*Martindale* slot cleaning outfit. It consists of grinding disc, electrical shaft and motor drive. It is used to clean old insulation out of armature slots when rewinding armatures, and also to remove old solder from the riser slots.

Likewise the rebanding is ordinarily done with the armature in a lathe, at a speed and at bandwire tension depending upon the size and peripheral operating speed of the armature and the kind of bandwire used.

The removal of banding wire, slot sticks and coils and the replacing of such parts must be done in a manner so as to avoid injury to the insulation. Coils of large size or with special high temperature insulation should preferably be heated as described for A.C. coils, before handling in order to prevent cracking of insulation.

Rewinding of Small Power D.C. Armatures Having Partially Closed Slots

Armature Types.—There are a number of distinct types of armatures and each of these types uses different methods of windings. The principal types are:

1. Bipolar.
2. Four pole.

The smaller or fractional horsepower of bipolar armatures using wire from No. 20 B & S and finer are nearly always wound by machine.

Medium sizes using wire to about No. 16 are sometimes encountered in automotive work. These are wound both by hand and by machine.

Large bipolar armatures of integral horsepower sizes are occasionally machine wound, although most frequently wound by hand. These are sometimes form wound and coils assembled.

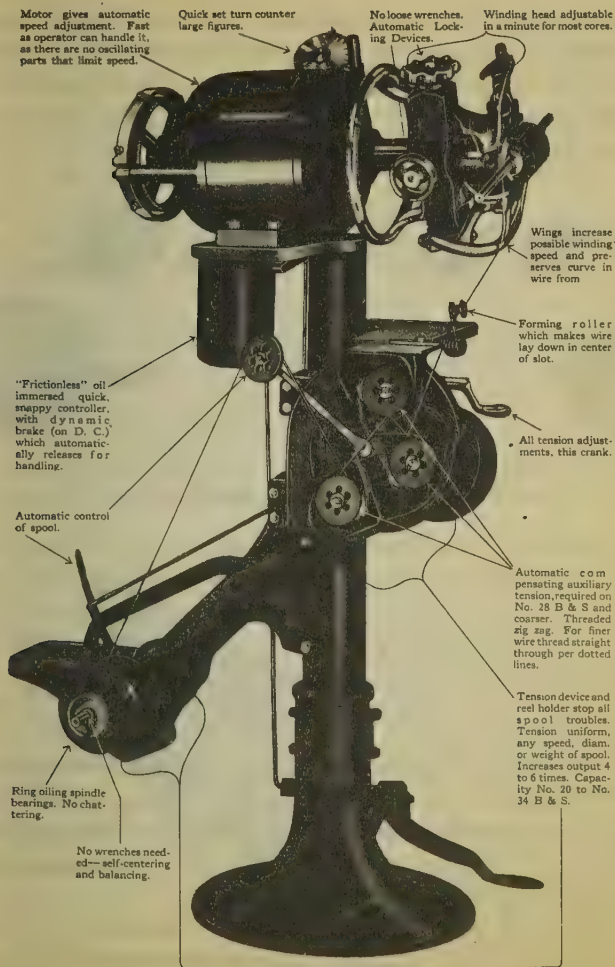
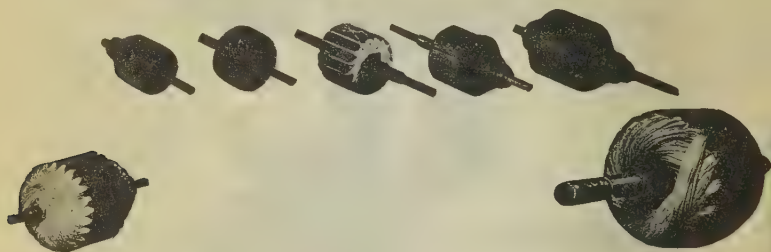


FIG. 4.—Illustrating *Chapman* style 3, adjustable bipolar drum armature winding machine.

Four pole armatures in fractional sizes using wires from No. 16 to 18 are alternately hand and machine wound. These are wound directly on the core, or prewound and coils assembled.

In the integral sizes, *preformed* and more or less *pre-insulated* coils are nearly always used.



FIGS. 5 TO 11.—Showing various types of armatures wound on machine, shown in fig. 4.

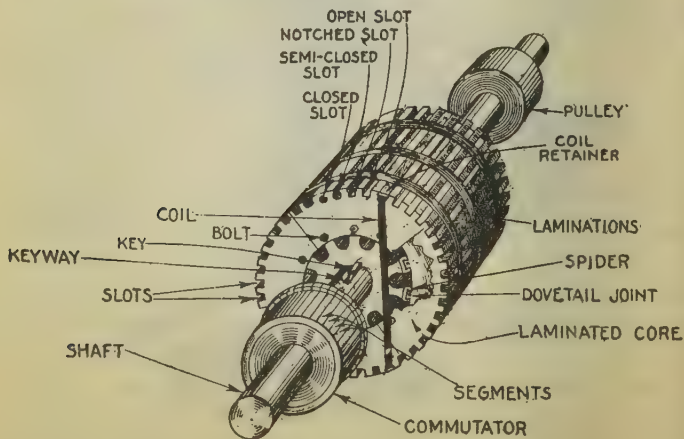


FIG. 12.—Direct current armature with names of parts.

Preparing the Core.—If the core is damaged or unsuited for the winding it may be necessary to remove the old core completely. The new laminated punchings are slipped on one at a time over the spider and key. On the smaller machines the first three or four laminations at each end are made of heavier steel and serve to stiffen the core and prevent vibration. At one end they are held in position by a collar on the spider arm.

After the core is assembled with laminations and ventilators in their proper order, the end frame which holds them at the other end is placed in position, the core is compressed in a jig by a heavy screw until the key slots on the spider and the end frame coincide, and ring keys are inserted into these slots, holding the core rigidly in place. The assembled core and spider are then pressed onto the shaft.

In the smaller machines the commutator is usually pressed on the spider before the armature is wound.

Winding the Coils.—Each complete coil may contain three or four single coils of double cotton covered wire wound from separate reels into one unit.

The leads of each single coil are provided with extra insulation in the form of woven cotton sleeves which as a distinguishing mark are of different color on each pair of leads.

In winding the coils, a sleeve to protect the leads is first slipped down to the end of each wire and adjusted so that it will reach about three-quarters of an inch along the body of the coil, the ends of the wires being fastened on the mould. As the spindle is revolved slowly, the operator guides the wires into the mold, placing the strips of tape under them at the corners, and keeping them under considerable strain to make them conform closely to the shape of the mould.

On the last turn another sleeve is slipped down each wire to protect the leads, extending along the body of the coil a suffi-

cient distance to be bound in place with the tape which was previously inserted. The leads are then cut off at the proper length.

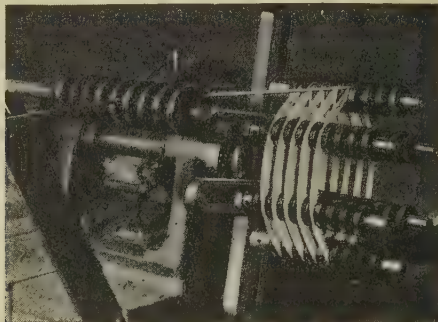


FIG. 13.—Illustrating a series of diamond coils being wound on typical coil winder head.

Inserting Coils in Slots.—The slots should be insulated with an outer protective layer of fish paper as described in Chapter 21.

On machines having a terminal voltage of 500 volts or over, it is customary to insert a third cell of treated cloth, which is placed next to the fish paper cell, and enclose both the coils, insulating them more fully from the core. These cells are cut to such a width that they will project about an inch beyond the slot openings, thus serving to guide the strands into the slot, and to protect them from mechanical injury during the winding operations.

Since the slots are partially closed, all the bottom coils can be inserted as shown in figs. 14 and 15 before the top coils are placed in the slots. The individual strands are forced into the slot with a flat fibre drift. As each coil is put in place, the

lower leads are inserted into the slits of the proper commutator bars, care being taken that the different colored leads are connected always in the same order.

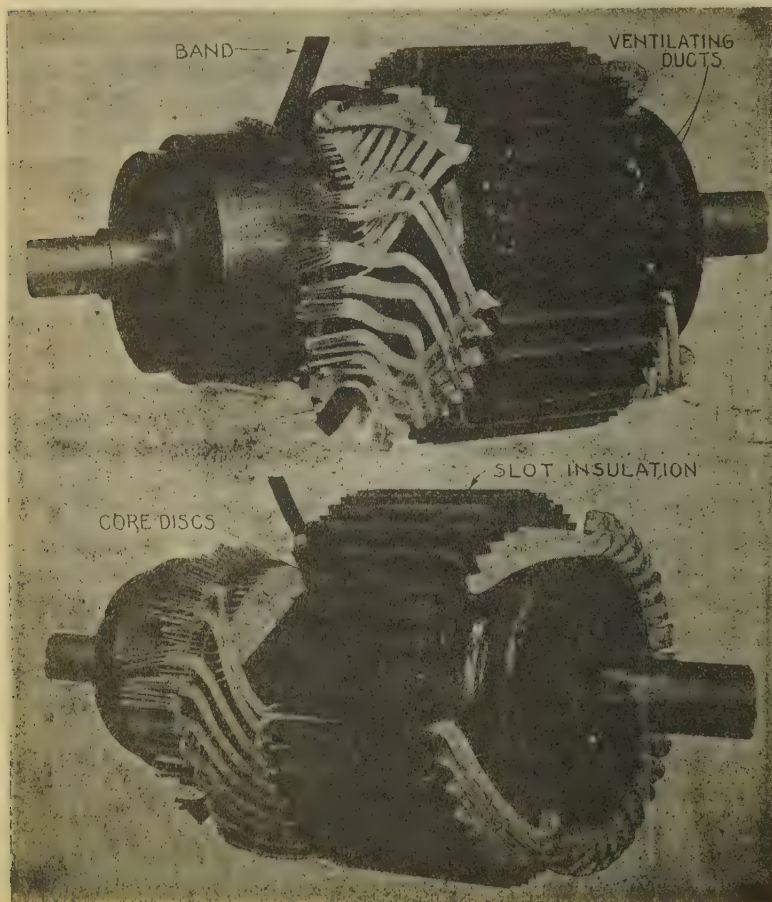
After all the coils are in position in the lower half of the slot the projecting edges of the inner cell enclosing the lower coil are cut off close to the slot and folded in, using the fiber drift and a mallet to force the wires and cell into position in order to make room for the upper coil. The unprotected wires which cross the end of the core are then taped with cotton tape for about two-thirds of their length, starting up close to the core and enclosing the ends of the lower cells which project from the slot.

After all the lower slots have been filled, an upper cell is inserted in one of the slots to receive the top coil. Facing the commutator, the throw is counted in a counter-clockwise direction from the slot just prepared, to determine which coil should go into this slot. The proper coil is bent into better shape; its strands are then waxed and inserted into the slot. The edges of the projecting cell or cells are then clipped, folded in and hammered tightly into place with a mallet and drift.

A fiber wedge is then driven in over the coil, by means of the wedge driver shown in fig. 17. This wedge driver consists of a hollow rectangular piece of steel, fitted with a sliding steel strip of about the same size as the wedge. The wedge is inserted into the driver, its end is then beveled and started into the slot and it is driven into position by tapping the steel strip with a mallet. A piece of cotton tape is then firmly wrapped around the coil and the projecting tip of the wedge closed up against the core to insure the end connections out to the taping previously placed in position, the end of the tape being glued.

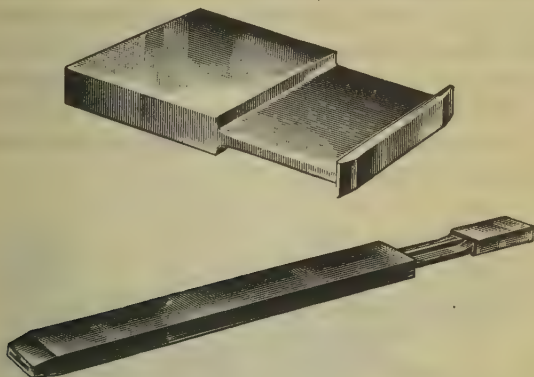
After two or three of the top coils have been placed in position, one or more treated duck strips are inserted between the end connections of the upper and lower coils, where they cross

each other at the ends of the armature, as shown in fig. 14. As the upper coils are put in place these strips are wound around



FIGS. 14 and 15. Showing two views of wave wound armature with strap coils being placed in the slots. (Courtesy General Electric Co.)

the armature so that they finally form a complete band of insulation between the upper and lower coils. Each coil as it is put in place is shaped at its ends with a mallet and drift so that all coils nest snugly one against the other and present a rigid construction when the armature is completed.



Figs. 16 and 17.—Showing typical coil tamping tool and wedge driver, respectively.

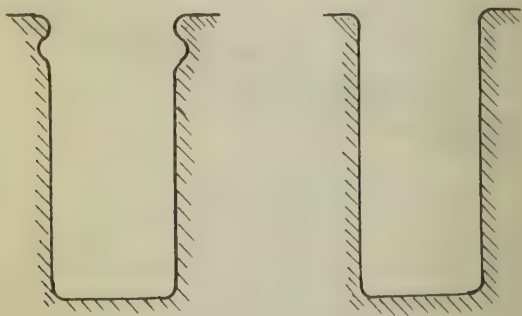
Connecting to the Commutator.—Before soldering the leads to the commutator bars, tests should be made for open circuits, short circuits and grounds. If trouble is noted, it should be corrected immediately. When everything is found satisfactory, the armature is prepared for soldering by wrapping tape around the ends of the leads at the point where they enter the commutator. The commutation connections are then soldered, care being taken that no solder gets on the leads in the rear of the bars.

After completion of the soldering operation the commutator is turned and finished with sandpaper. The armature is now ready for banding.

Rewinding of Small and Medium Size D.C. Armatures Having Open Slots

Open slot machines in sizes of over five horsepower may be wound with coils made up of either wire or strap copper.

The two types of slots generally employed are shown in figs. 18 and 19. Fig. 18 has wedge grooves in the teeth, through which wedges can be driven, thus securely holding the coils in position. With the slot shown in fig. 19, the banding wire is wound in the banding grooves of the armature and is relied upon to keep the coils in the slots.



FIGS. 18 and 19.—Illustrating open slots with and without wedge grooves, respectively.

One standard core of the open slot type may be used with several types and sizes of machines. The only change usually necessary to adapt it to a slightly smaller coil, is to fill in the slots on the sides and below the coils so that the wedges or banding wire will press firmly against the top of the coils in the slots, thus preventing any motion of the coils which may chafe the insulation. The *fillers* usually consist of strips of treated fullerboard.

The laminations are weighed out and assembled by placing one by one over the spider in the same manner as that previously described.

Type of Coils.—The coils may be of the mold wound, former wound or pulled type and are fully insulated before being inserted into the slots.

The coils in most general use are the wire wound short type and strap wound diamond type.

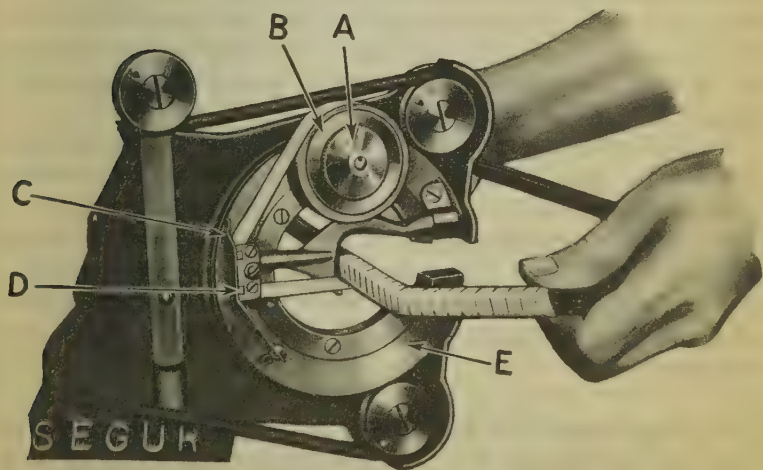


FIG. 20.—Illustrating method of taping an armature coil. Note how the coil is held against self-feeding device which relieves strain on operator and assists in securing uniform lap on tape. Roll of tape is placed behind tension plate *B*, and adjusting nut *A*, and fed under tension spring *C*, and tension plate *D*. Tension on roll of tape is regulated by adjusting nut *A*. Shuttle *E* should revolve clockwise.

The insulation is applied to the coils after they leave the coil winder, who merely ties them with a string, so as to hold the strands in place, though in some cases a thin paper cell is pasted around the body of the coil by the winder. A standard insulation for small machines consists of a wrapper of treated cloth over the body of the coil, held in place by a non-overlapping layer of cotton tape, and the leads are further protected by cotton sleeves. The entire coil is then dipped in insulating varnish and baked.

The wave winding is almost universally used on the smaller types of direct-current machines of multi-polar construction. This winding has but two paths through the armature, regardless of the number of poles, and half the coils in the armature are connected in series in each path, whereas the lap winding has as many paths as there are poles, and a correspondingly smaller number of coils in series.

Assuming, for instance, two four-pole armatures wound with coils of the same number of turns and same size conductors; if all are connected in a wave winding, the armature will be suitable for double the voltage at half the current that would be used with the same armature connected for a lap winding. Thus on small machines, where the number of turns is necessarily limited, the wave winding is usually much cheaper and easier to install.

Inserting Coils.—To facilitate inserting the coils the core is mounted horizontally in a special winding stand or lathe, and the slots are filled with fish paper cells according to specifications. These fish paper cells should be about one quarter of an inch longer than the slots, and wide enough to project about an inch above the entrance of the slots. These form a mechanical protection for the coils and also act as guides or runways through which they can be easily slid into place.

The corners of the projecting edges are cut off to keep them from interfering with the insertion of the coil. The winder inserts a coil in two slots whose separation is determined by counting off the specified throw, and forces the side that is to go into the lower part of the slot into position by laying a flat fibre drift over it in the slot and tapping it with a mallet.

If it does not fit snugly, side fillers of fullerboard or wood should be inserted so that there can be no possible motion. A coil is then fitted similarly into the adjacent slot and so on around the armature until coils equal in number to the throw minus one have been put in place. The upper side of the next coil inserted will then fall in the same slot as the lower side of the first coil placed in the armature.

Each slot, when the coils are all in place, will thus contain two separate coils, one above the other. Each top coil is driven firmly into place with the drift and mallet. The edges of the cell are then cut off, and if wedges are employed to hold the coils in the slots, the sides of the cell are bent over so as to get them under the wedge, which is then driven into place, making a tight fit in the grooves and bearing down hard on the coils.

The end connections are shaped by means of a winding drift. This consists of a steel bar about 12 inches long, one inch wide, and tapered in thickness from one-half to one-eighth inch, having all the corners rounded and smooth. The tip of this drift is placed against the inner side of the end connection of the coil and tapped with a mallet, forcing the upper part of the end connection out from the armature, and away from the lower half.

Each coil as it is put in place is similarly shaped so that when the armature is completely wound a circular air chamber is formed between the upper and lower halves of the end connections at both front and rear. This process is continued until the first slot is again reached. This slot and several succeeding ones contain a top coil but no bottom one.

These coils, called the throw coils because they cover a part of the armature equal in number to the throw, must be removed, as they are being retained in their approximate position by the other side of the coil, which is in the bottom of a slot. The bottom coils are then put in place and the throw coils are replaced and wedged into a permanent fit. After all the coils are in place the winding is trued up and tested for ground. A friction cloth blanket is then placed over the end connections on the commutator end, as a protection for the leads.



FIG. 21.—View of completed armature.

When wedges are not used to keep the coils in place, some means must be provided to prevent them from becoming loosened from the slots during the subsequent operations before banding. To accomplish this, a single band of wire is tightly fastened around the coils at each end of the armature.

In most machines of this type the commutator is pressed on the spider after the winding is in place. The leads are then connected to the commutator, and copper wedges are driven into the slits over the leads to hold them in place. The commutator is then soldered, turned and polished, and the armature is banded. After being balanced and tested, the armature is painted and is then ready to be mounted in its frame.

Rewinding Large D.C. Armatures

In rewinding large armatures the process of dismantling discussed in the beginning of this chapter should be observed. Although the design of the various types of D.C. machines differ in many particulars mechanically, the winding process, however, is essentially similar.

The Coils.—These are nearly always formed of bare copper strap. They are usually of the one piece one turn diamond type, there being as many coils as there are commutator bars. To secure better space factor, however, and for other design and mechanical reasons, two or more single coils are bound together into a mechanical unit, the individual coils of which are insulated from one another and electrically separated so that the number of slots is only a fraction of the number of bars.

The method of insulating this type of coil depends on the size, voltage and operating conditions of the machine and on the number of single coils composing a complete coil. When there are less than four single coils per complete coil, the ends of each single coil are taped with one layer of cotton tape, half overlapping.

This taping extends a sufficient distance along the straight part to assure that the joint between it and the rest of the insulation will be well protected. The straight parts are then wrapped with a fish paper and mica wrapper, which is interwoven between the straps in such a manner as to furnish insulation between the single coils and is then wrapped several times around the complete coil, the exact number of turns depending on the size, voltage and operating conditions of the machine.

When there are four or more single coils per complete coil, alternate single coils are wrapped with one turn of fish paper and mica, held in place by a non-overlapping layer of cotton tape. The single coils are then assembled and a cell of fish paper and mica wrapped over the whole. The coil is then taped with a layer of cotton tape, non-overlapping over the wrapper and half lapped over the ends.

It is then brushed with, or dipped in black finishing varnish and dried in an oven for twelve hours after each immersion. Before it is ready for use in the armature, the leads are cleaned of insulation and varnish and thoroughly tinned.

Armature Cross-Connections.—Nearly all direct current machines of the larger sizes are wound with a *lap* or *multiple circuit winding*. This means that there are as many circuits through the winding as there are poles each generating current under a separate pole, and all connected in parallel through the brushes. As it is practically impossible for the voltages generated in these circuits to be exactly equal, there is a tendency for short-circuit currents to flow through the windings and the brushes.

These currents have a tendency to equalize the flux values under the poles so that equal voltages will be generated in all the circuits. However, their maximum effect is halfway between the poles, so that their magnitude is practically limited only by the resistance of the windings and brushes. These equalizing currents cause overheating of the conductors, and sparking at the brushes, and thus reduce the capacity of the machine.

By connecting together points of equal polarity on the different circuits by means of a special connection between the windings and the commutator, the short-circuit current is removed from the brushes entirely.

In addition it is alternating in character, and out of phase from the main current by a large angle, so that a comparatively small current serves to build up or cut down the magnetic fluxes under the various poles until approximately equal voltages are generated in all the armature circuits.

As originally used, the equalizing windings consisted of two or more rings of copper wire or strap, from which taps were led to equi-potential points on the windings. The present tendency, however, is to equalize at as many points as possible, and this can be best accomplished by a series of cross connections.

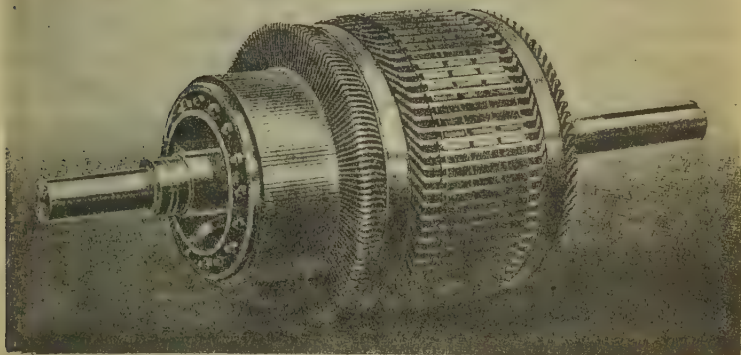


FIG. 22.—Armature of 150 kw. direct current motor.

A form of connection which lends itself readily to this purpose, and occupies very little space is shown at the rear of the armature in fig. 22. It consists of a strap of copper bent to an S shape at the center as shown in the illustration. The insulation is usually the same as that on the end connections of the

armature coils. The leads are tinned and are riveted and soldered to taps taken from the rear end of the coils. This form of connector is generally bound in place with heavy twine.

An equalizing connector of the same shape as the diamond end of the armature coils is somewhat easier to install than the type shown, and can be connected at shorter intervals; it is, therefore, very extensively used. The copper strap is bent edgewise into a flat loop, which is then pulled sideways into its finished form. Two or three of the connectors are generally bound together into a mechanical unit, using the same insulation that is used on the armature coil ends. The leads are brought out at suitable intervals and tinned.

This type of connector is frequently used at the front of the armature, where it rests on a special coil support. This support is insulated with fullerboard, and enclosed in a cell of drilling, part of which is laid back over the armature, until the windings are connected. The leads are slipped into openings in the commutator necks at regular intervals, the top of one connector going into the same neck with the bottom end of another, so that a number of complete rings are formed around the armature, with taps to the winding at similar points under each pole.

Wooden wedges are driven between the necks, tight enough to force them into intimate contact with the leads, after which the leads are soldered into place, and the projecting ends are cut off close to the face of the necks. A test is then applied for short circuit between adjacent connectors to be sure that the solder has not followed along the necks and short-circuited the commutator bars.

The drilling is then folded back over the connectors, a band of fullerboard enclosed in a cell of friction cloth is wound over this, and the whole is finally bound in place by band wires. The connectors are then tested for grounds. This test must be very

carefully made at this time, as these connectors are covered by the main windings, and are difficult to repair after the latter are in place. Both types are used to considerable extent, depending on the characteristics of the machine.

Rotary converters are equalized in the same manner as the direct current generators. No special equalizing connections are made, however, to those coils which are connected to the collector rings as the collector rings serve the same purpose;

Winding the Armature.—In a *wave* or *two-circuit winding*, all the coils between two diametrically opposite points on the winding are in series with one another, while in a *lap winding*, only the coils between adjacent pole centers are in series. Thus, other conditions being equal, the voltage in a wave winding will equal the voltage in a lap winding multiplied by the number of pairs of poles, and the voltage between commutator segments will vary in the same ratio.

To secure the same voltage for the machine, it is evident that the relative number of coils in the two types must vary inversely with the number of poles, and the size of the coils in the wave winding must increase in proportion.

The wave winding has the decided advantage that no cross-connections are required. It has, therefore, a very extensive application on machines in which the size of coil does not become excessive, nor the voltage between segments too great to allow of good commutation.

Ordinarily, however, this consideration limits the use of this type of winding to four or six pole machines, and, where the number of poles is greater, the lap or multi-circuit type of winding is universally used on direct current machines. With this winding, not only is the voltage between segments kept down to reasonable limits, but great conductivity through the armature can be readily secured without using coils of excessive cross-section.

Both types of windings are ordinarily wound with one piece coils. Two piece coils have, however, some advantages and are used to a certain extent; less care and skill is ordinarily required in the winding operation, and there is no need of removing any of the coils after they have been once placed in a slot, as must be done with the throw coils of the one piece type.

Also the windings can be more easily repaired if the top half of the coil only is damaged. On the other hand a soldered joint is necessary at the rear of the armature, which requires considerable time and skill, and on the larger machines, where a winding jig is impracticable, it is difficult to secure a symmetrical shaping of the rear end of the armature.

Insulating the Core.—As a preliminary to the winding operations the core is thoroughly cleaned with an air blast, thus removing any iron fillings or other foreign matter from the slots. The commutator necks are then carefully examined to see that all are straight and that the openings at the top are wide enough to admit the coil leads easily. The commutator is tested for breakdown to ground, and for short-circuit between segments, with the standard test voltage for the machine.

All parts of the spider which come in contact with the coils, such as coil supports, etc., are carefully insulated with either tape, fullerboard channels, or two or three thicknesses of fullerboard strips. When tape is used, it is wrapped in overlapping layers over the entire support. At the point where the spurs which hold the coil support in position prevent winding on the tape, the iron is covered with cloth, which is held in place by the tape on each side. Each layer of the tape is shellacked as it is wound.

When fullerboard strips are used, the first layer is frequently screwed to the iron to prevent lateral motion. Other layers are shellacked over this, and the whole is usually bound with twine. Special care is taken to stagger all joints.

Inserting the Coils.—The assembly of the different types of coils is essentially similar. Two slots are marked with chalk to receive the first coil, and the commutator necks into which its leads will be connected are counted off and marked. Fish paper cells are inserted into the slots, and the coils are driven into position one after another, with a mallet fiber drift. If a two piece coil is used, the lower half-coils are inserted first, all the way around the armature, and then the upper half coils.

If one piece coils are used, the coils are inserted in regular succession, the bottom half of the coil being driven into the bottom of its slot first. The other half is driven into close contact with the coil which is already in the bottom of the slot. If there is no coil in the bottom of the slot, as happens with the throw coils, this top half is inserted only temporarily until the winding has been carried entirely around the armature, when the throw coils must be removed so that coils can be placed in the bottom of the slots.

When a one piece coil is used in a wave winding, the throw coils span so large a part of the armature that it is not usually advisable to insert the upper part of the coils into the slots and then remove them again. The coils are, therefore, allowed to hang free, as shown in fig. 23, until all coils have one side in place. The upper parts can then be driven into their permanent position in regular order.

The upper and lower coil ends are separated by bands of oiled duck or drilling. With one piece coils this is threaded in place as the coils are inserted. With two piece coils it is simply

wound over the lower set of coils before the others are placed in the slots.

With certain types of coils, where the coil ends do not fit closely together, U or L shaped pieces of treated fullerboard are placed over both the upper and lower coil ends, thus separating the adjacent coil ends, as well as the upper and lower layers. In some cases, these strips are placed over the ends by the coil winder and covered with the last layer of tape. This makes the winding very compact at the ends.

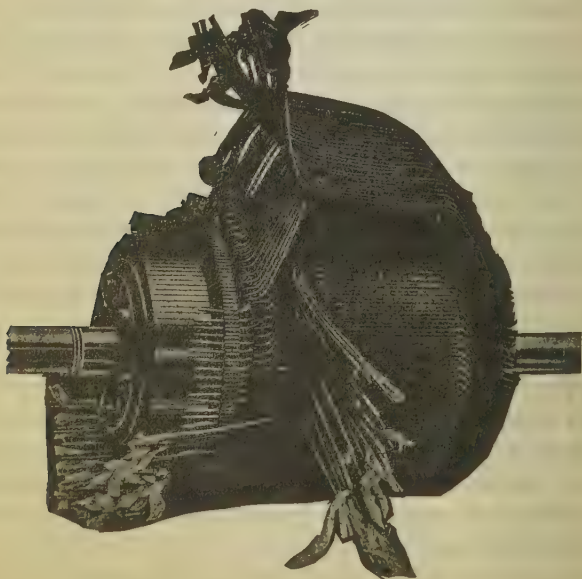


FIG. 23.—Wave wound armature partially completed.

The coils must be a close fit in the slots, in order to prevent any possibility of chafing. If necessary strips of fullerboard or treated wood are inserted at the sides or bottom of the slot, to make the coils a tight fit. As each top coil is put in place, it is driven into the slot, the protecting cells are cut off, and folded over it, and fiber wedges are driven into the wedge grooves.

The slots on a large sized machine are too long to allow one wedge to be used, so one or more are driven in from each side of the slot, furnishing complete protection for the face of the coil. The armature is then tested for grounds, before the connections are soldered.

After the winding is completed, the armature is banded temporarily at both ends. Wooden wedges are then driven in between the commutator necks, being first driven in loosely all around the armature to insure even spacing and then driven in tightly, forcing the necks and coil ends into tight contact and holding them rigidly in place.

With two piece coils, connecting clips are placed over the leads at the rear end, and wedges are driven in between these in the same manner. The connections to the necks, and the rear end connections, if any, are then soldered. This soldering is always done on the side of the machine instead of the top, as a better joint can be made in this manner, and there is less liability of the melted solder running along the necks and short circuiting the commutator segments.

Before removing the wedges the armature is mounted in a lathe, or if no suitable lathe is available, in its bearings with the field frame removed, and the soldered connections are turned down. If the armature is mounted in its bearings, a suitable tool holder must be fastened to the frame, or some rigid support. The commutator is also turned down and given its final

polishing at this time. The wedges are then knocked out from between the leads, and the sharp corners are rounded off with a file.

The bare copper is not covered with insulation, but insulating material is sometimes inserted between the adjacent leads to prevent accidental contact. At the rear end, this usually takes the form of asbestos tape which is interwoven between the leads, or of canvas hoods, sewed in place. At the front end, the necks may be separated at the tops by strips of heavy fish paper, bent over the tops of the leads so as to be held in place by the band wires. Where the necks are quite long, additional separators are inserted about half way up from the commutator. These may be in the form of fiber buttons or may merely consist of heavy twine, interwoven between the necks.

Rewinding A.C. Stators

Removing Stator Coils.—To rewind or replace a portion of the winding, remove slot wedges and start removal of coils by lifting a sufficient number of coil sides in the top of the slot to uncover and allow removal of preceding coils. In the case of large coils, it is desirable to warm coils to be lifted to approximately 45° C. prior to lifting to increase flexibility of insulation and minimize possibility of cracking and damage.

As a rule, this first group of top coil sides are each lifted a little at a time so that the entire group is raised, more or less as a unit. This method avoids interference between coil sides and ends as coils are raised and eliminates necessity for possible excessive bending. Extreme care must be taken in lifting coil sides to avoid damaging insulation by sharp bending or by mechanical abrasion.

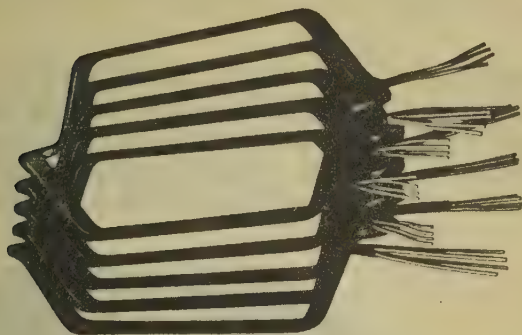


FIG. 24.—Typical form wound stator coils with class A insulation. (Courtesy Allis Chalmers Mfg. Co.)

Preparation of Slots.—Clean slots thoroughly and repaint core with air dry insulating varnish before placing new slot cells and coils.

Slot cells of 0.010 in. varnish treated paper are usually used; cells extend $\frac{3}{8}$ in. beyond core iron at each side of core and are cut wide enough to extend several inches beyond surface of core to facilitate entrance of coil into slot. Additional slot cells or slot side fillers of varnish treated paper are added when placing coils to insure tightness of coil in the slot.

Sufficient thicknesses of varnish treated fibre 0.030 in. less than the width of the slot and 2 in. longer than the length of the core are added between top and bottom coil sides to build top coil side within 0.010 in. or 0.020 in. of the slot wedge notch. If space allows, it is also desirable to place a 0.010 in. or 0.020 in. varnished fibre filler between the bottom of the slot cell and the bottom of the slot in order to insure cushioning any irregu-

larities in the bottom of the slot. Filler in bottom of slot should be cut 0.010 in. less than width of slot and $\frac{3}{4}$ in. longer than core.

Replacing Coils.—Coils are to be carefully placed in slot and tapped in placing, using a soft cushioned hammer and a fibre block slightly less than the width of the slot and approximately one inch longer than the core. The application of a thin coat of paraffin or other wax to the surface of the coil at the time of

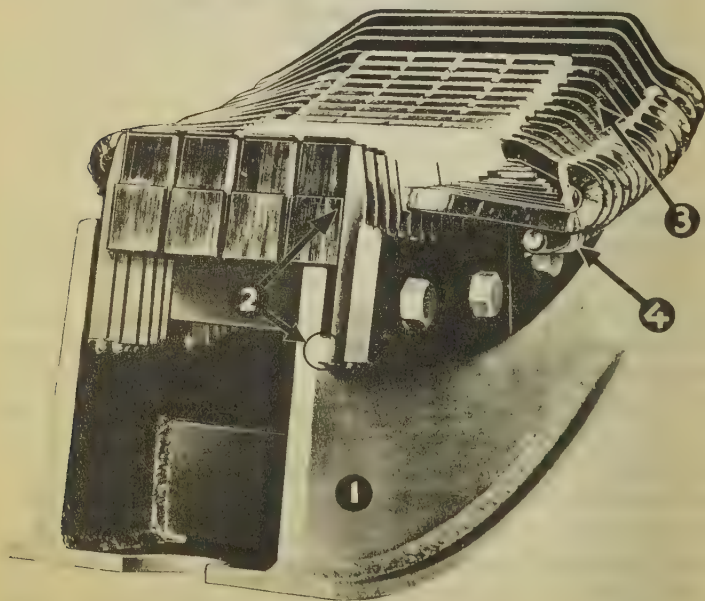


FIG. 25.—Cutaway section of large synchronous motor frame. In the illustration 1 indicates frame construction; 2, core clamping; 3, solidly built up insulation on stator coils, and 4, coil end blocking and bracing. (Courtesy Electric Machinery Mfg. Co.)

winding greatly aids in placing the coil. Considerable care and judgment must be exercised when placing the coil in the slot since coil must be placed tightly but must not be damaged.

Cording and Blocking.—If coil end supports or coil end cording or blocking is used, the required cording and blocking should be done on each coil as it is wound. A good grade of strong non-stretching linen cord should be used. Cording should be painted with a heavy coat of air dry insulating varnish.

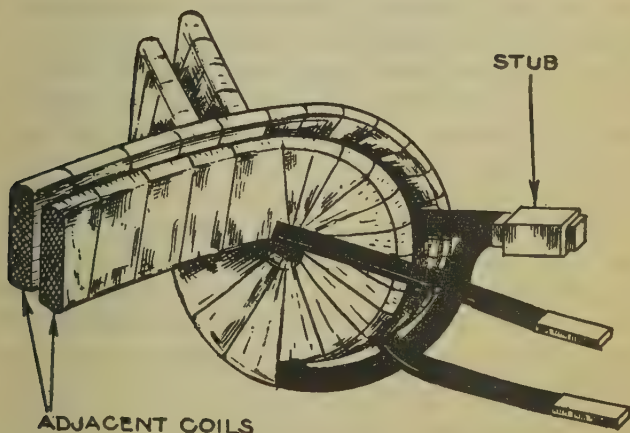


FIG. 26.—Showing method of making stub connections between adjacent coils. Before the jumpers between polyphase groups can be attached, the coils in each group must be connected in series by connecting the starting lead of one coil to the finishing lead of the adjacent coil. This is commonly known as *stubbing-up* the winding.

After coils have been placed in the slot and the coils which have been lifted to enable lapping of the winding have been treated and placed back in the slot, slot cells are to be cut off flush with the coil side in the top of the slot.

Slot cells may also be cut so as to lap on top of the coil under the slot wedge; however, since the cell is primarily to protect against mechanical abrasion during assembly of coil and since full ground insulation is on coil itself, the edges of the cell are usually cut flush with the top surface of the top coil side.

Placing Slot Wedges.—Slot wedges are to be cut sufficiently wide to be reasonably tight when fitted into the wedge notch without the coil in the slot. Wedges are to be relatively short in length, 4 in. to 8 in. to facilitate handling and driving. Sufficient varnish treated fibre fillers similar to those used between coil sides are to be added under the wedge to insure a tight coil and a tight wedge. Wedges in each half of slot are to be driven in from their respective end of the core.

On vertical machines, several layers of cotton tape or cord are to be placed around coil ends at bottom of core in such a manner as to prevent the slot wedges and fillers under the wedge, between coils and at the bottom of the slot from falling out in case they loosen during subsequent operation of the machine. Cotton tape or cording is to be given several coats of air dry insulating varnish.

Making Connections.—Series, phase and machine lead connections are to be tinned, bound securely together with tinned copper wire, and soldered using a 50% tin, 50% lead solder. Connections should be long enough to be strong mechanically and should have a contact area at least 5 times the cross sectional area of the conductor. When tinning and soldering,

care must be taken not to burn insulation and to prevent soldering flux from getting on insulation. Clean soldered connections before insulating, removing rough solder projections, flux and dirt.

Series, phase, and machine lead connections are to be insulated with 1 layer of $\frac{1}{2}$ in. lapped 0.006 in. cotton tape, the number of layers of 0.007 in. varnished cambric tape as indicated in Table I, and 1 layer of $\frac{1}{2}$ in. lapped 0.006 in. cotton tape. Each layer of cotton tape and varnished cambric tape are to be given a heavy coat of air dry insulating varnish as they are applied.

TABLE I

Machine Voltage	Series Leads	Phase and Machine Leads
0-1,500 V, Incl.....	2	3
1,501-3,100 V, Incl.....	3	4
3,101-4,200 V, Incl.....	4	5
4,201-5,200 V, Incl.....	5	7
5,201-6,100 V, Incl.....	6	8
6,101-7,000 V, Incl.....	7	9

NOTE.—Series connection is coil to coil connection. Phase connection is coil group to coil group connection. Machine load connection is terminal lead connection.

Phase connections and machine leads are to be securely corded together and to series leads and coil ends to provide mechanical support and to prevent movement and vibration. Use a good grade of linen cord.

Varnish treat completed winding either by dipping and baking several times in a good grade of baking varnish or spray or paint winding with several coats of good air dry insulating varnish. If dipping and baking procedure is used, baking temperature should not exceed 135° C.

Rewinding Wound Rotors

Replacing Rotor Coils.—The general statements made in regard to replacing of stator coils also apply to the same operation on the rotor coils.

On large wound rotor motors a wave winding is universally used with the coils clipped together at the ends. The slots are of the semi-closed type. When the rotor coils are made, they are insulated in the slot portion and shaped and insulated at one end. The other end is left straight for inserting into the semi-closed slots.

After placing the rotor coil in the slot the straight end of the coil is shaped and completely insulated. Normally, a slot liner is used on the slot portion of the coil. The coils are securely wedged into the slot by adequate spacers and by driving a slot stick in the top of the slot above the coil.

Spare Parts Coil and Winding Material

Spare Coils.—The time a machine is out of service for repairs can often be reduced if a supply of spare coils and rewinding material is maintained for such an emergency. The number of such parts to be kept in reserve will depend upon the machine, the number of duplicate machines, the operating hazards, and the degree of necessity for continuous service.

For large machines, replacements for one or two pole pitches, including the necessary slot sticks and rewinding material, is frequently a reasonable number of spares. For smaller machines, with fewer and relatively cheaper coils, one-quarter of a set of stator coils is often satisfactory.

Generally, machines operating at the higher voltages are more subject to lightning and switching surges, and a greater number of spare coils is desirable. On the other hand, machines with a large number of coils can frequently be operated temporarily, in the event of damage to one or two coils, by cutting out the damaged coils and similarly located coils in the other phases and circuits until new coils can be secured from the factory.'



FIG. 27.—Showing stator partly wound with factory made coils. Coils of the type shown can be readily purchased from motor manufacturers ready for installation, and will speed up motor repairs when used.

Handling of Coils.—Mica insulated stator coils must be handled very carefully when rewinding a machine. The throw coils and the coils to be inserted should be heated to 40°C . or 45°C . in order that they may be sufficiently flexible to bend as required without cracking the insulation.

The number of spare rotor coils for wound rotor induction motors and for armatures of D.C. machines should usually be about the same as the number of spare stator coils.

Field coils for synchronous and D.C. machines gradually deteriorate with age, but they are not usually subjected to the same hazards as the stator winding and seldom require replacement without warning unless operating conditions are very unfavorable. One spare field coil, with pole insulation and collars, is usually satisfactory.

Spare coils should be stored until needed in their shipping boxes in a cool dry place where the temperature is not subject to wide and abrupt changes. In ordering spare coils, be sure to give the complete name plate rating of the machine and particularly the serial number.

Winding Tools

Use of Winding Tools.—There are certain tools which are essential to the successful winding of any type of machine. In addition to these, certain types of winding require tools which have been especially developed to meet the specific needs. An experienced winder will in some cases develop his own tools, or at least modify them to meet his personal requirements. The tools illustrated in figs. 28 to 38 are, however, sufficient for most windings of A.C. stators.

The following instructions for the proper use of tools should be carefully noted:

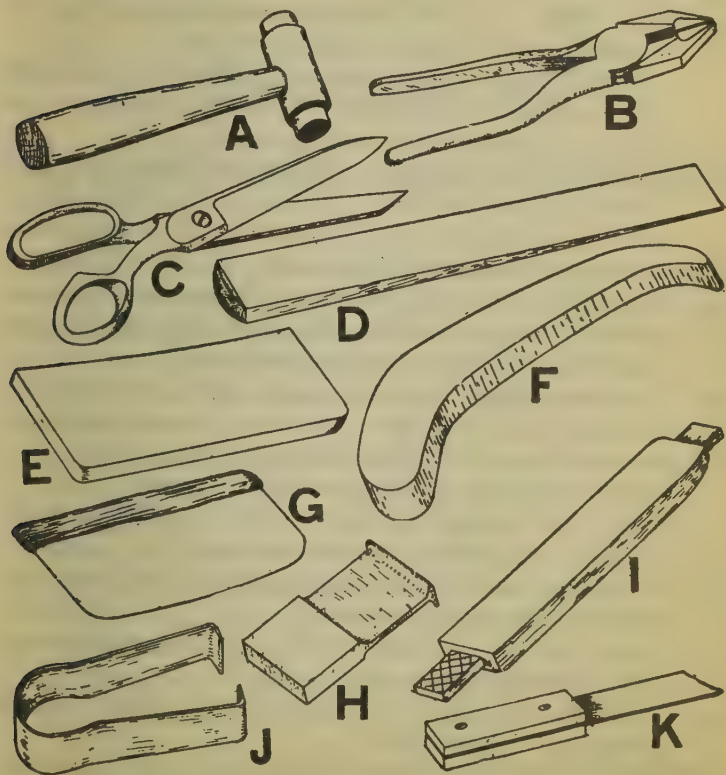
1. When striking hard blows on tools other than fibre, be careful not to roughen the surface of the rawhide face.

Avoid striking the coils a hard blow directly with the mallet—use a drift or shaper. A blow from a mallet is concentrated on a small spot. A drift distributes the effect of the blow and avoids damage.

2. Pad the jaws of the pliers with tape, when using them to grasp insulation.

Do not use pliers in place of a cold chisel.

3. Use scissors solely to cut insulating cloth, and thin insulating materials.



FIGS. 28 to 38.—Hand tools ordinarily used in winding induction motors. These are: *A*, rawhide mallet; *B*, pliers; *C*, scissors; *D*, steel winding drift; *E*, assorted thicknesses of fibre slot drifts; *F*, fibre shaping drift; *G*, fibre cell drift; *H*, steel T-shaped cell drift; *I*, wedge driver; *J*, lead scraper; *K*, knife.

Avoid using scissors in place of pliers or scraper. Do not bend the points by prying with them, as they will cut poorly after being bent, no matter how sharp their edges.

4. Keep smooth all surfaces that come in contact with the coil; nicks in a drift leave corresponding scars on the insulation when used in shaping the coil.

Never use a steel hammer on that part of the drift that comes in contact with insulation in shaping the coil—use nothing but a rawhide mallet.

5. Slot drifts should have flat square faces with their corners slightly rounded. Always use the same edge of the drift to pound on. This will leave the other edge smooth for contact with the coil. As the coil edge of the slot drift becomes rounded from use have it filed or ground flat, as a flat edge offers the largest surface and distributes the blow over the coil better.

Always use the thickest possible drift, as a thick drift is easier on the coil than a thin one. Never use a piece of metal instead of fibre for a slot drift with which to drive the coil down into the slot.

6. Keep the shaping drift smooth and free from nicks. Pound it only with a rawhide mallet.

Do not use the fibre shaping drift on anything but coils, and insulating materials.

7. Use a fibre cell drift, and that only, for threading wires into a partially closed slot.

Do not use a piece of metal for a cell drift. Do not pound on the fibre drift.

8. The T-drift is used in packing the insulating spacer between the top and bottom coils in partially closed slots.

CHAPTER 29

Banding of Armatures and Rotors

General.—The primary purpose of banding as applied to armatures of direct current machines and wound rotor induction motors is to hold the winding securely in place. The centrifugal forces acting on the winding elements particularly in the case of high speed machines with surface speed in excess of 8,000 feet per minute are very large, thus necessitating the use of band wires of high tensile strength and extreme care and workmanship in its application to the armature.

Banding of Small Direct Current Armatures.—Before proceeding with the banding operation it is customary to insert the armature in a lathe or a special armature holder similar to that shown in fig. 1.

The actual operation is usually performed in the following step-by-step procedure:

1. Hammer down the ends of the coils with a mallet until the diameter of the wire ends coincides with that of the armature core. Care should be taken not to injure the coil insulation with the mallet.

2. The band insulation usually consists of two bands of cotton tape, separated by a band of varnished paper, wound over the end connections near the core and tied down with several layers of twine. Next short clips of tinned copper sections are slipped under the temporary banding twine at intervals of two to three inches, with two extra sections inserted where the wire is started and terminated.
3. The actual banding wire commonly used is No. 14 to 17 B. & S. gauge tinned steel wire of high tensile strength. The beginning (start) of the banding wire is usually secured to the end of the banding twine, and the first layer is guided so that it crosses itself, thus relieving the strain of the end fastening. After two or three turns of the armature and the band wire, the temporary banding twine may be cut off and the banding wire wound on tight, with the adjacent turns of the banding wire touching one another across the protecting tape layers.
4. After the required width has been wound (its width depending upon the size of the armature) the copper strips at the starting end should be turned up and cut off so that about one quarter inch projects from under the banding wire. Then bend the strips over to hold the banding wire in position.
5. The band on the opposite end of the armature is wound in a similar manner without cutting the banding wire and to within about a quarter of an inch of the edges of the end connections. The clips at the beginning and end may now be bent over and soldered. The balance of the clips are then crimped over the band and the entire band soldered.

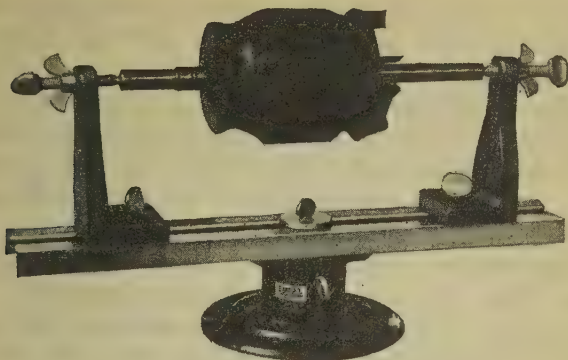


FIG. 1.—Typical armature holder suitable for banding small armatures. The base is made in two sections—the lower or stationary part which fastens to a bench top, and the upper portion of the base which supports the cross arms for the upright casting. The upper section pivots on the stationary part and freely rotates, permitting the work to be turned to the most desirable position. A thumb screw locks the rotating member to the stationary base.

Banding of Large Machines

Band Wire.—The band wire as specified for direct current armatures and wound rotor induction motors is designed to resist the centrifugal force of the coil ends and insulation, allowing a conservative factor of safety. The band wire must be applied with an initial tension in excess of that caused by the maximum speed of the machine in order to prevent any movement or chafing of the coils.

Three grades of band wire are used:

1. Steel having a tensile strength of 210,000 lbs. per sq. in.
2. Austenitic, non-magnetic steel with a tensile strength of 210,000 lbs. per sq. in.
3. Phosphor bronze having a tensile strength of 120,000 lbs. per sq. in.

The wire is tinned to facilitate soldering and must possess such toughness as to be bent through 180° flat upon itself without cracking.

Non-magnetic steel band wire is used on wound rotor induction motors and on D.C. armature having a peripheral speed of over 5,000 feet per minute. Plain steel band wire is used on armatures having a peripheral speed of less than 5,000 feet per minute. The use of phosphor bronze wire has been largely discontinued in favor of non-magnetic steel, which, while more expensive, has far superior mechanical qualities. Non-magnetic steel band wire is usually not available on the market but may be obtained from the manufacturer of the electrical machinery.

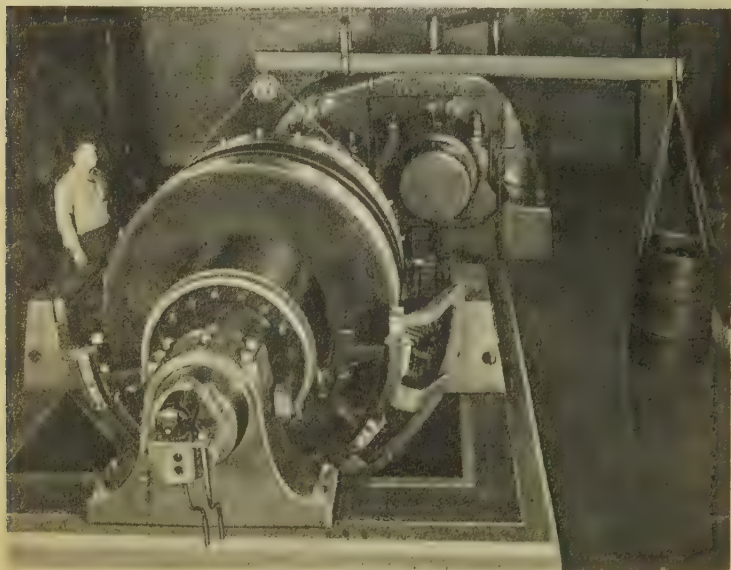


FIG. 2.—Illustrating banding the armature of a 2,500 h.p. D.C. motor for steel mill service.
(Courtesy Allis-Chalmers Mfg. Co.)

Band Insulation and Clips.—The band insulation consists of one layer half-lapped eight ounce (0.025 inch) varnished ducking and 0.013 inch fish paper cut in pieces six inches long and one-half inch wider than the band and applied together with the fish paper next to the band. In the case of class *B* insulation, one layer of half-lapped 0.005 inch mica folium, is applied next to the coils in addition to the foregoing.

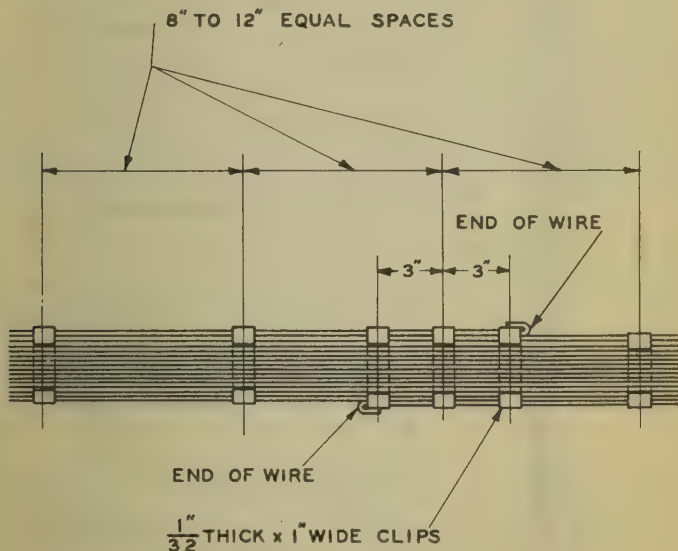


FIG. 3.—Illustrating spacing of band wire clips.

The band wire clips are made of $\frac{1}{32}$ inch by one inch wide copper or tinned steel and are spaced eight to twelve inches apart, using the following rule: The number of clips must be an odd number, that is, not a multiple of any common divisor of the number of poles on the machine or closer than 10% (more or less) of the number of poles. For example, on a six-pole

machine the number of clips used could be 7, 11, 13, 17, etc. Three clips are placed at the ends of the wire about three inches apart, as illustrated in fig. 3.

The insulation and the clips are held in place with a few turns of cotton tape before starting the band.

When it is desired to subdivide the band to prevent eddy currents, a piece of flexible mica 0.020 inch by two inches wide is placed under three or four turns and then folded up to separate the turns at the designated place for the complete circumference, as shown in fig. 4. The projecting part is trimmed after the band is completed. When the band is subdivided, it is also necessary to insulate the clips from the band with 0.005 inch mica folium cut one-half inch wider than the clip and as long as the band is wide.

The bands should have a slight dip at the center of the section to prevent them from moving end-ways. In order to form the dip it is necessary at times to wrap the coils with varnish-treated cotton tape under the band wire insulation.

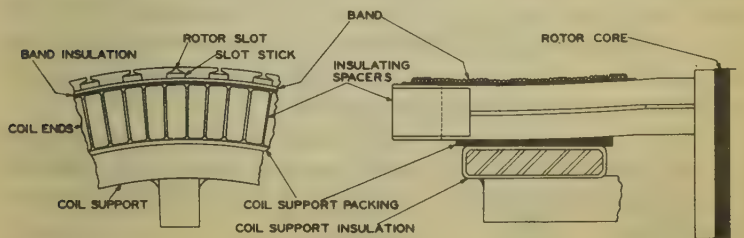


FIG. 5.—View of the coil ends of a slip ring type induction motor, showing spacers between coil ends under the band.

If the coil ends of slip ring type induction motors show a tendency to twist or bend when being banded, spacers of insulating material should be inserted between the coil end clips in sufficient number to form a rigid arch of the coil ends and spacers when the band is tightened. See fig. 5. The use of these spacers prevents the coil ends from turning over and allowing the band to slip off.

Baking Coils.—The best results are obtained by heating the coils before banding to make the insulation more flexible so as to allow the coils to be pressed into place more easily and uniformly. The armature or rotor is heated either in an oven or by internal circulating current until a uniform temperature of 200° F. is obtained throughout. The band is then applied while the coils are hot.

Temporary Banding.—Temporary banding, in general, is unnecessary when the permanent band is applied as described later in this chapter. However, in cases where the coils must be pressed to an unusual extent, a temporary band may be required. The coils are protected by using 0.040 inch fuller board under the band. At the end of the temporary band, the wire is anchored and the armature is allowed to cool to room temperature. Then the temporary band is removed, and the insulation and final bands are applied.

When it is necessary to press the coils down in their slots, hardwood strips should be placed over the coils in the slots and a band wound over these strips with a helical pitch of two to three inches.

Banding Procedure.—The starting end of the band is anchored by attaching a cord, which has been wound around

the armature, to a hook bent in the end of the wire and by crossing the second turn a number of times over the first.

In addition the first two turns may be soldered together. Three or four extra turns are added at each end of the regular band, see fig. 4. Adjacent turns of the regular band should touch, but the extra turns are set off a half inch or more. Where the extra turns run off the band insulation, the coil ends should be protected by placing 0.040 inch fuller board under the band wire. Both ends of the armature may be banded in one continuous operation. The wire is run on the armature with just enough tension to hold it in place. At the end of the band, three turns are run over a two-inch by four-inch by about four-inch long wood block laid on edge which can be removed to pick up slack in the wire. The final end of the wire is soldered to the adjacent turn and to a clip.

Tension Control.—It is of the utmost importance that the correct degree of tension be uniformly applied to the band. The device as shown in fig. 6 and described later should be used to obtain uniform and accurate wire tension. The component parts can be easily procured on location for any banding job.

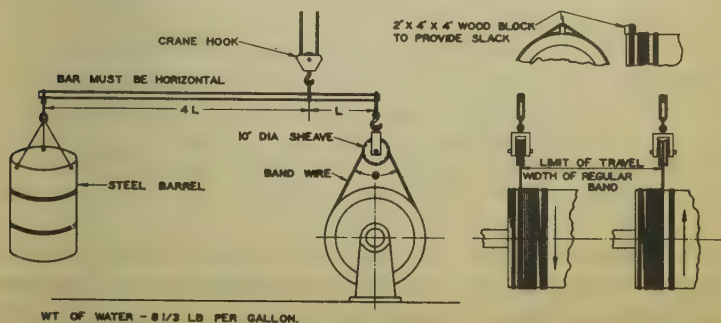


FIG. 6.—Illustrating band wire tension device.

The device consists of a timber, pipe, or light I-beam, one end of which carries a standard steel drum, such as an oil barrel, and the other end a sheave of at least ten inches diameter.

The beam is suspended from a crane hook, chain hoist or block and tackle at a point one-fifth of the span from the sheave end. A beam ten feet in length is commonly used with the point of suspension two feet from the sheave support and eight feet from the barrel support. Water is added to the barrel to obtain the required loading, as shown in the table I.

The loading given in the table represents the total load required at the end of the beam, including the weight of the barrel and one-third of the weight of the beam.

TABLE I
TOTAL LOAD AT END OF BEAM INCLUDING WEIGHT OF BARREL
AND $\frac{1}{3}$ WEIGHT OF BEAM

Band Wire			Steel							Phosphor Bronze						
			Tension in Wire		Load on Beam—Lb.					Tension in Wire		Load on Beams—Lb.				
			Force Lb.	Stress Lb./ Sq. In.	Angle of Wire Over Sheave					Force Lb.	Stress Lb./ Sq. In.	Angle of Wire Over Sheave				
B.&S. Gage	Dia. In.	Area Sq. In.			0°	30°	60°	90°	120°			0°	30°	60°	90°	120°
8	.1285	.01295	850	66000	425	410	368	300	212	600	46000	300	290	260	212	150
10	.1019	.00817	600	73500	300	290	260	212	150	400	49000	200	193	173	141	100
12	.0808	.00512	400	78000	200	193	173	141	100	250	49000	112	108	97	79	56
14	.0641	.00322	250	78000	125	121	108	88	63	160	50000	80	77	69	56	40
16	.0508	.00203	160	78000	80	77	69	57	40	100	50000	50	48	43	35	25

After the band wire has been wound on the armature as previously stated, the wood block is removed, and the slack thus provided is used to pass the wire over the sheave while the barrel is resting on the floor or on blocks. The tension device

is lifted by means of the crane so that the beam is approximately horizontal with the barrel suspended free of other support. The included angle of the wire over the sheave is estimated and the loading adjusted accordingly. The armature is slowly turned to run the sheave across the width of the band and then reversed to run the sheave back to the starting point.

Slack Removal.—This process is repeated, raising the tension device as slack is removed from the wire so that the beam remains approximately horizontal. If the angle of the wire over the sheave changes appreciably, weight must be added to correct the loading. The sheave should not be run into the extra turns provided at either end of the regular band, as to do so may cause the temporary fastening of the wire to give way.

When no further slack can be taken up, the sheave is stopped just outside the regular band, and two clips are bent over and soldered at each end of the band. Then the tension is relieved, and the surplus turns of wire are cut off and removed. The ends of the wire are bent in the form of a hook over the third end clip, tripped and soldered in place.

The balance of the clips can then be crimped over the band and the entire band soldered. The clips are bent over about three turns of the band. All wires are sweated together and to the clips to make a homogeneous unit of the band.

The solder used should contain 50% or more tin. The melting point of solder ranges from 358° F. for a mixture of 50% lead and 50% tin to 450° F. for pure tin. When the soldering iron is in contact with the band wire, it should be kept in motion; for, if it is allowed to rest on the wire, annealing and consequent reduction in strength of the wire may take place.

This is very important when phosphor bronze band wire is used. The maximum temperatures to which the various kinds of wire may be safely heated are:

Phosphor bronze	450° F.
Plain steel	600° F.
Non-magnetic steel	1,000° F.

A soldering iron may be heated as high as 900° F. without oxidizing the tinned surface of the iron.

CHAPTER 30

Armature Calculations

The purpose of this chapter is to present a brief outline of the more important factors which enter into the design of a D.C. machine. It may be said at the outset that accurate design is a matter of both calculation and experience because many of the factors involved cannot be determined by calculations alone.

In the design of a D.C. generator or motor, it is customary to first design the armature and make the other parts to conform with it. The principal items to be considered is the kilowatt capacity, the voltage, speed allowable temperature rise, and the requirements of the service to which it is to be adapted.

In order to deliver a certain current, at a given voltage, the number of poles, etc., being fixed, a certain size of wire must be used. As must be evident, the heating of the wire is the determining factor that governs its size. For a given current the smaller the wire the greater the heating will be.

The e.m.f. Equation.—It is generally well known that the *e.m.f.* induced in a conductor depends on the rate of cutting the magnetic flux, and is equal in volts to the number of magnetic lines cut per second divided by 10^8 . In any ordinary armature a number of such conductors are connected in series and their *e.m.f.*'s are, therefore, added. It can be proved that the average induced *e.m.f.* in a direct current armature is equal to:

$$E = \frac{P \phi Z N}{60 \times 10^8 \times P'} \text{ volts} \quad (1)$$

Where

P = number of poles

ϕ = total useful magnetic flux per pole

Z = total number of armature conductors or sides of coils

N = revolutions of armature per minute

P' = number of parallel conducting paths between the positive and negative brush sets

The values of P' for different types of windings are given below.

	Lap Winding	Wave Winding
Simplex	$P' = P$	$P' = 2$
Duplex	$P' = 2P$	$P' = 4$
Triplex	$P' = 3P$	$P' = 6$
Quadruplex	$P' = 4P$	$P' = 8$

Since for a given machine all factors except ϕ and N are constant, let

$$K = \frac{PZ}{60 \times 10^8 \times P'} \quad (2)$$

Then
$$E = K\phi N \quad (3)$$

This shows that the generated *e.m.f.* in a machine is directly proportional to the flux per pole and the speed.

The Output Equation.—Another equation readily obtained from the *e.m.f.* equation is written as:

$$\frac{\text{Watts}}{N} = \frac{ZI_a}{\text{Paths}} \times \phi \times P \times \frac{1}{60 \times 10^8} \quad (4)$$

Where ZI_a/Paths , termed the electric loading is the total number of ampere-conductors on the armature periphery.

The following practical examples will be of assistance in showing how the various formulas may be employed.

Example.—A generator has 4 poles, with faces 6 inches square and has a flux density in the air-gap of 40,000 lines per square inch. The machine has 360 conductors and the winding is simplex lap. Compute the e.m.f. of the generator when driven at 1,200 r.p.m.

Solution.—Since the winding is simplex lap, $P' = 4$ and from equation (1)

$$E = \frac{4 \times 40,000 \times 6^2 \times 360 \times 1,200}{60 \times 10^8 \times 4} = 103.7 \text{ volts. } \textit{Ans.}$$

Example.—A 6-pole simplex lap-wound generator has 240 armature conductors. The flux per pole is 3,000,000 lines and the e.m.f. generated is 144 volts. Calculate the speed in r.p.m.

Solution.—By using formula (1), we obtain

$$N = \frac{E \times 10^8 \times 60 \times P'}{\phi Z P} = \frac{144 \times 10^8 \times 60 \times 6}{3 \times 10^6 \times 240 \times 6} = 1,200 \text{ r.p.m. } \textit{Ans.}$$

Example.—A certain 6 pole generator has 310 armature conductors. The flux per pole is 4.5×10^6 lines and the speed 1,000 r.p.m. Calculate the electromotive force when the conductors are connected to form

- (a) A simplex wave winding.
- (b) A duplex lap winding.

Solution.—Substituting values in formula (1), we obtain

(a)

$$E = \frac{6 \times 4,500,000 \times 310 \times 1,000}{60 \times 10^8 \times 2} = 697.5 \text{ volts. } \text{Ans.}$$

(b)

$$E = \frac{6 \times 4,500,000 \times 310 \times 1,000}{60 \times 10^8 \times 12} = 116.25 \text{ volts. } \text{Ans.}$$

Example.—A six pole simplex lap-wound generator has 300 armature conductors. The 100 square inch pole area has a density of 50,000 maxwells per square inch, and the speed of the armature is 900 r.p.m. Calculate the induced voltage.

Solution.—

$$E = \frac{P \phi Z N}{60 \times 10^8 \times P'}$$

$$= \frac{6 \times 50,000 \times 100 \times 300 \times 900}{60 \times 10^8 \times 6} = 225 \text{ volts. } \text{Ans.}$$

Example.—An eight pole generator has a triplex wave-wound armature, with a total number of turns = 80. At a speed of 600 r.p.m. and a flux per pole of 14×10^6 lines, calculate the armature e.m.f.

Solution.—

$$E = \frac{P \phi Z N}{60 \times 10^8 \times P'} = \frac{8 \times 14,000,000 \times 80 \times 600}{60 \times 10^8 \times 6} = 149.3 \text{ volts. } \text{Ans.}$$

Example.—It is required to design an 8×8 armature, for a flux of 30,000 lines per sq. in., 110 volts, 1,200 r.p.m., 5 horse-power. Determine size of wire required for the armature, number of turns, etc.

Solution.—Cross sectional area of armature = $8 \times 8 = 64$ sq. ins.

Total flux through armature = $30,000 \times 64 = 1,920,000$ lines.

Now, since it requires 10^8 or 100,000,000 lines of force cut per second to generate one volt, for the given 110 volts, the required rate of cutting is

$$\frac{\text{required rate of cutting}}{\text{total flux}} = \frac{110 \times 100,000,000}{1,920,000} = 5,729 \text{ lines per sec.}$$

The number of inductors (wires) necessary to place on the armature to cut 5,729 lines per second will depend on the speed, thus

number of inductors =

$$\frac{\text{total lines per wire per sec.}}{\text{revolutions per sec.}} = \frac{5,729}{\frac{1}{60} \text{ of } 1,200} = 286$$

For five horse power, at 110 volts

$$\text{watts} = 746 \times 5 = 3,730; \text{ amperes} = \frac{3,730}{110} = 34$$

Since there are two paths through the armature in parallel,

$$\text{amperes per circuit} = 34 \div 2 = 17$$

The size wire to be used is based upon a certain radiating surface per unit of energy consumed. The greater this radiating surface, the less will be the heating. The amount of radiating surface allowed in armatures varies from 1 sq. in. per watt to 3 sq. ins. About 1.75 will insure a cool operating armature. In the accompanying tables, the current capacity is given for 3 sq. in. and for 1 sq. in. per watt. An inspection of the tables will show that the capacity of wires depends also upon

TABLE I.—3 sq. ins.

*Capacity of Wires at various depths of winding, 3 sq. in. radiating surface per watt
(According to Horsmann and Tousley)*

B. & S. Gauge.	Diameter bare.	Resistance per foot 140° F.	Diameter D. C. C.	Amperes at different depths of winding layers.					Number of wires per inch.	1's
				1	2	3	4	5	6	
4	.2043	.000283	.224	56.28	39.74	32.42	28.12	25.15	22.97	3166
5	.1819	.000357	.200	47.30	33.46	27.33	23.66	21.16	19.31	2240
6	.1620	.000450	.180	40.00	28.28	23.08	20.00	17.98	16.34	1600
7	.1413	.000567	.158	33.40	23.60	19.28	16.67	14.93	13.63	1114
8	.1285	.000715	.144	28.35	20.04	16.37	14.17	12.68	11.57	805
9	.1144	.000902	.130	24.00	16.97	13.35	12.00	10.72	9.74	576
10	.1019	.001137	.117	20.27	14.31	11.70	10.14	9.05	8.24	411
11	.0907	.001436	.106	17.19	12.12	9.69	8.60	7.68	7.00	295
12	.0808	.00181	.093	14.31	10.09	8.24	7.14	6.40	5.83	205
13	.0719	.00228	.084	12.12	8.54	7.00	6.08	5.38	4.89	147
14	.0640	.00288	.075	10.19	7.21	5.91	5.09	4.58	4.12	104
15	.0570	.00362	.067	8.60	6.08	4.95	4.30	3.87	3.50	74
16	.0508	.00458	.059	7.14	5.04	4.12	3.57	3.19	2.91	51
17	.0452	.00575	.053	6.08	4.30	3.5	3.04	2.64	2.47	37
18	.0403	.00727	.048	5.09	3.60	2.94	2.54	2.28	2.08	26
19	.0358	.00916	.044	4.36	3.08	2.52	2.18	1.97	1.78	19
20	.0319	.01153	.040	3.74	2.64	2.16	1.87	1.67	1.52	14
21	.0284	.01454	.036	3.14	2.22	1.81	1.57	1.39	1.28	9
22	.0253	.01845	.033	2.66	1.87	1.54	1.33	1.19	1.09	7.1
23	.0225	.0231	.030	2.28	1.61	1.30	1.14	1.01	.94	5.2
24	.0201	.0295	.028	1.94	1.37	1.14	.97	.86	.80	3.8
25	.0179	.0365	.026	1.70	1.18	.98	.85	.80	.74	2.9
26	.0159	.0461	.024	1.41	1.00	.82	.71	.63	.57	2.0
27	.0143	.0603	.022	1.18	.78	.68	.59	.52	.47	1.4
28	.0126	.0744	.021	1.04	.72	.60	.52	.47	.42	1.1
29	.0112	.0925	.020	.92	.65	.52	.46	.42	.38	.86
30	.0100	.1181	.019	.77	.54	.44	.38	.35	.31	.61

TABLE II.—1 sq. in.

Capacity of Wires at various depths of winding, 1 sq. in. radiating surface per watt
(According to Horstmann and Tausley)

B. & S. Gauge.	Diameter bare.	Resistance per foot 140° F.	Diameter D. C. C.	Amperes at different depths of winding layers.						Number turns per inch	12
				1	2	3	4	5	6		
4	.2043	.000283	.224	97.36	68.75	55.88	43.64	43.50	39.73	4.45	9498
5	.1819	.000357	.200	81.82	57.88	47.27	40.87	36.60	33.40	5.00	6720
6	.1620	.000450	.180	69.20	48.93	39.92	34.60	30.93	28.28	5.5	4800
7	.1413	.000567	.158	57.78	40.82	33.35	28.91	25.86	23.60	6.3	3344
8	.1285	.000715	.144	49.04	34.66	28.87	24.57	21.97	20.07	7.0	2416
9	.1144	.000902	.130	41.52	29.37	24.00	20.76	18.60	16.97	7.7	1728
10	.1019	.001137	.117	35.06	24.81	20.27	17.54	15.71	14.35	8.6	1233
11	.0907	.001436	.106	29.74	21.02	17.17	14.86	13.80	12.12	9.6	885
12	.0808	.00181	.093	24.79	17.52	14.31	12.40	11.09	10.09	10.7	615
13	.0719	.00228	.084	21.00	14.86	12.12	10.50	9.38	8.54	11.9	441
14	.0640	.00288	.075	17.66	12.49	10.19	8.83	7.88	7.21	13.3	312
15	.0570	.00362	.067	14.89	10.53	8.60	7.44	6.66	6.08	15.0	222
16	.0508	.00458	.059	12.40	8.77	7.21	6.20	5.56	5.09	17.0	154
17	.0452	.00575	.053	10.53	7.44	6.08	5.26	4.71	4.30	19.0	111
18	.0403	.00727	.048	8.88	6.28	5.12	4.44	3.97	3.63	21.0	79
19	.0358	.00916	.044	7.54	5.34	4.35	3.76	3.37	3.08	22.7	57
20	.0319	.01153	.040	6.49	4.58	3.74	3.24	2.89	2.64	25.0	42
21	.0284	.01454	.036	5.68	3.80	3.11	2.68	2.40	2.19	28.0	29
22	.0253	.01845	.033	4.58	3.24	2.64	2.28	2.04	1.87	30.3	21
23	.0225	.0231	.030	4.00	2.82	2.30	2.00	1.78	1.64	33.8	16
24	.0201	.0295	.028	3.37	2.38	1.94	1.67	1.51	1.37	35.7	11.4
25	.0179	.0365	.026	2.93	2.07	1.67	1.44	1.30	1.18	38.4	8.6
26	.0159	.0461	.024	2.49	1.76	1.44	1.22	1.09	1.00	42.0	6.2
27	.0142	.0603	.022	2.07	1.44	1.18	1.04	.94	.84	45.5	4.3
28	.0126	.0744	.021	1.78	1.26	1.04	.89	.78	.71	48.0	3.2
29	.0112	.0925	.020	1.61	1.14	.94	.79	.71	.65	50.0	2.6
30	.0100	.1181	.018	1.34	.95	.78	.64	.60	.55	56.0	1.8

the kind of winding—whether single layer or more than one layer—because radiation is more effective in carrying off the heat with outside wires than with those embedded under an outer layer of wires.

Now, since the diameter of the core is 8 ins.

$$\text{its circumference} = 8 \times 3.1416 = 25 \text{ ins.}$$

and the number of inductors per inch of circumference is

$$\text{for single layer winding } 286 \div 25 = 11.4$$

$$\text{for double layer winding } \frac{1}{2} \text{ of } 286 \div 25 = 5.7$$

Allowing 3 sq. ins. radiating surface per watt, the size of inductor required to carry 17 amperes is (from Table 1 on page 992).

for single layer winding, No. 11, B. & S. gauge

for double layer winding, No. 9, B. & S. gauge

Example.—*With the armature of the previous example running at same speed and same flux conditions what is the maximum capacity that could be obtained with a two layer winding of larger size wire and same number of inductors?*

Solution.—As calculated, the number of inductors per inch of core circumference is 5.7, hence, from table 1, for 5.5, inductors per inch a No. 6 wire may be used, and for a two layer winding it may carry 28.28 amperes. Now since there are two paths in parallel through the armature

$$\text{total current} = 2 \times 28.28 = 56.6 \text{ amperes}$$

and capacity at 110 volts, or

$$\text{watts} = 56.6 \times 110 = 6,226$$

Since 1 horse power = 746 watts,

$$\text{capacity} = 6,226 \div 746 = 8.4 \text{ horse power}$$

In the case of slotted armatures, which is the prevailing type, a considerable portion of the circumference is taken up with the teeth that cannot be used for the winding, hence it is necessary to allow for this in figuring the number of inductors per inch of circumference.

To calculate the size wire for a slotted armature a single slot should be considered, and the wire chosen if possible with reference as to how it will fit in the slot, that is, the size should be such as to fill the slot with the least amount of waste space. **In design**, the approximate width of the slot is obtained by *multiplying the diameter of the wire over insulation by the number of turns per layer*, and the depth of slot obtained by *multiplying the number of layers by .86*.

To find the number of inductors per slot when the speed and flux are fixed, the following formula may be used:

$$\text{inductors per slot} = \frac{10^8 \times \text{volts}}{\text{flux} \times \text{slots} \times \text{rev. per sec.}} \quad (5)$$

Example.—*How many inductors per slot are required, to generate 110 volts, with a total flux of 1,920,000 lines, 24 slots and 1,200 revolutions per minute?*

Solution.— $10^8 = 100,000,000$
and

$$1,200 \text{ rev. per minute} =$$

$$1,200 \div 60 = 20 \text{ rev. per sec.}$$

Substituting in (5)

$$\text{inductors per slot} = \frac{100,000,000 \times 110}{1,920,000 \times 24 \times 20} = 12$$

Example.—*If the slots of a 24 slot armature be $\frac{1}{2}$ in. wide, and there be 12 inductors per slot arranged as a three layer single coil winding, what is the maximum size wire that can be used, and current capacity for a four pole machine? If flux be provided to generate 110 volts what horse power will be developed?*

Solution.—Table 3 gives relation between slot sizes and various practical arrangements of standard double cotton wires B. & S. gauge. Allowance is made in the slot widths for $\frac{1}{8}$ in. total insulation besides the cotton wrapping on the wire, when there is only one coil per slot.

For each additional coil per slot, $\frac{1}{8}$ in. of extra insulation is allowed. In slot depths, .17 in. beside the cotton on the wire is provided.

In the example since there are 12 inductors per slot and the winding is in 3 layers

$$\text{number of wires abreast} = 12 \div 3 = 4$$

Referring to the table it will be found that a slot .42 in. wide will accommodate four No. 10 inductors abreast. Allowing 3 sq. in. radiation per watt, the carrying capacity (from table No. 1) for a 3 layer winding of No. 10 wire is 11.7 amperes.

Since the number of paths is equal to the number of poles

$$\text{total current output} = 11.7 \times 4 = 47 \text{ amperes}$$

At 110 volts

$$\text{watts} = 47 \times 110 = 5,170, \text{ and}$$

$$\text{horse power} = 5,170 \div 746 = 6.9$$

After having determined the size of wire, number of turns per coil, the drop or voltage loss due to the resistance of the winding should be determined to see if this loss be within limit.

Example.—If the average length per turn of the coils in the armature of the previous example be 2 ft., what is the drop or loss of voltage in the armature?

Solution.—Since the winding is of the single coil type each coil will occupy two slots, hence

$$\text{total number of coils} = 24 \div 2 = 12$$

For 12 turns per coil,

$$\text{length of each coil} = 12 \times 2 = 24 \text{ ft.}$$

Now, since the machine has 4 poles, there are 4 paths in parallel, hence, only $\frac{1}{4}$ of the coils or 3 coils need be considered in determining the drop. Accordingly,

$$\text{length of 3 coils} = 24 \times 3 = 72 \text{ ft.}$$

According to table 1 (page 992), the resistance of No. 10 wire at 140° F. is .001137 ohm per foot, hence

$$\text{resistance of 3 coils} = 72 \times .001137 = .08 \text{ ohm}$$

According to Ohms law

$$\text{current} = \frac{\text{volts}}{\text{ohms}}, \text{ or } \text{volts} = \text{current} \times \text{ohms}$$

Substituting in the expression for volts,

$$\text{volts or "drop"} = 11.7 \times .08 = .94 \text{ volt}$$

which may be considered within satisfactory limit.

Magnet Calculations.—In figuring field magnets, the unit ampere turn is frequently employed and is defined as *the magnetic force due to a current of one ampere flowing through one turn of a magnet winding*; numerically it is equal to the *product of one turn multiplied by one ampere*.

Thus, one ampere flowing through 10 turns, gives $1 \times 10 = 10$ ampere turns. Again, 10 amperes flowing through 10 turns gives $10 \times 10 = 100$ ampere turns. Having fixed the voltage and size of wire it makes no difference in the magnetic effect how many turns are contained in the winding, that is, for a given voltage and size of wire *the ampere turns remain the same regardless of the number of turns in the winding*.

Thus, if 10 amperes flow through 10 turns of the winding the result is $10 \times 10 = 100$ ampere turns. Now, if the number of turns be doubled, the resistance of the winding will be doubled which will cut down the current one half, that is, 5 amperes $\times 20$ turns = 100 ampere turns. Of course, this is not strictly true where the magnet is made up of more than one layer, because the diameter of an outer turn being greater than that of an inner turn, its length and resistance is greater, the resulting effect being to slightly decrease the ampere turns as each layer is added. The reason then for increasing the number of turns in a magnet winding is *to cut down the current sufficiently to prevent overheating of the winding*.

Example.—*If the winding on a spool 8 ins. in diameter be one inch thick, what is the average diameter of the turns?*

Solution.—The diameter of the inner layer turns is 8 ins., and the outer layer turns, $8 + 2 = 10$ ins., hence,

$$\text{average diameter of the turns} = \frac{1}{2} (8 + 10) = 9 \text{ ins.}$$

Example.—*If the magnet of the previous example contain 500 turns, what is the length of the winding?*

Solution.—The average diameter of the turns, as obtained, being 9 ins.

$$\text{length of winding} = \frac{9 \times 3.1416 \times 500}{12} = 1,178 \text{ ft.}$$

Example.—*If a winding one inch deep be placed on an 8 in. spool, what is the smallest size wire that will give 10,000 ampere turns with 110 volts?*

Solution.—

$$\text{average diameter of turns} = \frac{1}{2} (8 + 10) = 9 \text{ ins.}$$

$$\text{length of average turn} = \frac{9 \times 3.1416}{12} = 2.36 \text{ ft.}$$

The sectional area of the smallest wire (in circular mils) is obtained from the formula.

$$\text{area wire} = \frac{12 \times \text{length average turn in feet} \times \text{ampere turns}}{\text{volts}} \quad (6)$$

NOTE.—*To find the speed* when the volts, flux, and number of inductors are fixed, use this formula:

$$\text{rev. per sec.} = \frac{100,000,000 \times \text{volts}}{\text{flux} \times \text{number of slots} \times \text{inductors per slot}}$$

NOTE.—*To find the strength of field* when the volts, inductors and speed are, fixed, use the formula:

$$\text{flux} = \frac{100,000,000 \text{ volts}}{\text{inductors per slot} \times \text{number of slots} \times \text{rev. per sec.}}$$

NOTE.—*To find the volts* when the inductors, flux, and speed are fixed use the formula:

$$\text{volts} = \frac{\text{flux} \times \text{inductors per slot} \times \text{number of slots} \times \text{rev. per sec.}}{100,000,000}$$

Substituting

$$\text{area wire} = \frac{12 \times 2.36 \times 10,000}{110} = 2,575 \text{ circular mils}$$

nearest size wire from table is No. 16 B. & S. gauge.

Having determined the minimum size of wire, the next step is to find how many turns must be placed on the spool to prevent undue heating.

The watts lost by the current heating the winding *is equal to the square of the current multiplied by the resistance*, that is

$$\text{watts lost} = \text{amperes}^2 \times \text{ohms}.$$

In proportioning the winding for depth and length, the depth of the winding must be such that there will be from 1 to 2 sq. ins. of surface per watt. With 1 sq. in. per watt, the magnet in operation will be "hot," and with 2 sq. ins., "warm."

Example.—*How much radiating surface (neglecting the ends) on a magnet whose outside dimensions are 9 ins. diameter, 6 ins. long?*

Solution.—Area outer cylindrical surface = $9 \times 3.1416 \times 6$
= 169.6 sq. ins.

Example.—*An 8 in. spool is to be wound with No. 16 wire to a depth of 1 in., which, as calculated in a previous example, is the smallest size wire that will give a required 10,000 ampere turns with 110 volts. How many turns of wire must be wound on the spool to prevent undue heating?*

Solution.—For winding magnets what is known as *magnet wire* is used, the wire generally having a single cotton covered insulation.

length of winding per inch of spool = $361 \times 2.36 = 852$ ft.
 and from table its resistance being 4.009 ohms per 1,000 ft.

resistance of winding per inch of spool = $\frac{852}{1,000}$ of 4.009 = 3.42 ohms.

The outside diameter of the winding being 10 ins.,
 radiating surface per inch of spool = $10 \times 3.1416 = 31.4$ sq. ins.

Now, in any electric circuit, the energy lost by heating the wire, or

$$\text{watts} = \text{amperes}^2 \times \text{ohms} \quad (7)$$

And if the coil be designed for "warm" working by allowing 2 sq. in. radiating surface per watt, then it must be so proportioned that

$$\text{radiating surface} = 2 \times \text{watts lost} = 2 \times \frac{\text{volts}^2}{\text{ohms}} \quad (8)$$

In order to determine the length of the coil, first find what resistance would be necessary if the winding were to consist of only the one inch portion just considered. To do this, solve equation (8) for resistance.

Thus

$$\text{ohms} = \frac{2 \times \text{volts}^2}{\text{radiating surface}} \quad (9)$$

$$\text{ohms} = \frac{2 \times 110^2}{31.4} = 770$$

Accordingly, since the resistance of the winding is proportional to its length,

$$\text{length of winding} = 1 \text{ in.} \times \frac{770}{3.42} = 226 \text{ ins.}$$

TABLE III.—*Properties of Insulated Wires*

(According to Horstmann and Tousley)

B. & S.	Single silk		Double silk		Dble. cotton		Resistance	I ² 3 sq. in. per watt. Cool	I ² 2 sq. in. per watt. Warm	I ² 1 sq. in. per watt. Hot
	Turns per inch	Radiating Surface	Turns per inch	Radiating Surface	Turns per inch	Radiating Surface				
40	193	.016	143	.022	90	.035	.273	.027	.04	.08
39	181	.017	133	.024	87	.047	.216	.036	.055	.11
38	169	.018	126	.025	84	.037	.172	.046	.07	.14
37	156	.020	119	.026	81	.039	.136	.070	.10	.20
36	143	.022	111	.028	77	.041	.108	.086	.13	.26
35	131	.024	104	.030	73	.043	.075	.13	.20	.40
34	120	.026	97	.032	69	.045	.068	.15	.23	.46
33	111	.028	91	.035	66	.047	.054	.22	.32	.64
32	101	.031	83	.038	63	.050	.043	.29	.44	.88
31	91	.034	77	.041	59	.053	.034	.37	.56	1.12
30	83	.038	71	.044	55	.056	.027	.54	.81	1.62
29	76	.041	67	.047	53	.059	.022	.72	1.07	2.14
28	68	.046	60	.052	48	.065	.017	1.0	1.5	3.00
27	63	.050	55	.056	45	.069	.014	1.3	2.0	4.00
26	56	.055	50	.062	41	.075	.011	1.9	2.8	5.60
25	50	.062	46	.069	38	.081	.0084	2.7	4.1	8.2
24	45	.069	42	.075	35	.088	.0070	3.5	5.3	10.6
23	41	.077	37	.083	32	.095	.0053	5.2	7.8	15.6
22	36	.086	34	.092	30	.104	.0042	7.3	11.0	22.
21	33	.094	31	.101	28	.113	.0034	10.	15.0	30.
20	29	.106	27	.113	25	.126	.0026	14.	21.	42.
19	26	.119	25	.126	22	.138	.0021	20.	30.	60.
18	24	.132	22	.138	21	.151	.0017	27.	40.	80.
17	21	.148	20	.154	19	.166	.0013	39.	59.	118.
16	19	.166	18	.173	17	.185	.0011	52.	78.	156.
15			16	.191	15	.204	.00083	70.	105.	210.
14			15	.213	14	.226	.00066	107.	161.	322.
13			13	.238	12	.251	.00053	149.	224.	448.
12			12	.267	11	.279	.00042	217.	325.	650.
11			11	.298	10	.311	.00033	301.	451.	902.
10			9.5	.329	9.1	.342	.00026	421.	632.	1264.
9			8.4	.370	8.1	.383	.00021	587.	880.	1760.
8			7.5	.414	7.3	.428	.00016	842.	1262.	2524.
7			6.9	.455	6.8	.468	.00013	1167.	1750.	3500.
6			6.0	.521	5.8	.534	.00010	1680.	2521.	5042.

CHAPTER 31

Tables and Data**Ohm's Law for direct current**

$$I = \frac{E}{R} \quad R = \frac{E}{I} \quad E = I \times R$$

where I = amperes;
 E = volts;
 R = resistance.

Formula for resistances in series

$$R_{(\text{Total})} = R_1 + R_2 + R_3 \quad \text{etc.}$$

Formula for resistances in parallel

$$R_{(\text{Total})} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \quad \text{etc.}}$$

Determination of frequency of an alternator

$$\text{Frequency} = \frac{N \times S}{2}$$

where N = the number of field poles;
 S = the speed of the armature in revolutions per second.

Fundamental frequency formula

$$f = \frac{1}{2\pi\sqrt{LC}}$$

where f = frequency in cycles per second;
 L = inductance of the circuit in henries;
 C = capacitance of the circuit in farads.

Inductive reactance formula

$$X_L = 2\pi fL$$

where X_L = inductive reactance;
 L = inductance in henries.

Capacitive reactance formula

$$X_c = \frac{1}{2\pi fC}$$

where X_c = capacitive reactance;
 C = capacity in farads.

Ohm's Law for alternating current

$$I = \frac{E}{Z} \quad \text{or} \quad I = \frac{E}{\sqrt{R^2 + \left[\left(2\pi fL \right) - \left(\frac{1}{2\pi fC} \right) \right]^2}}$$

where I = current;
 E = voltage;
 Z = impedance (total of all oppositions).

Condensers connected in parallel

$$C_{(\text{Total})} = C_1 + C_2 + C_3 \quad \text{etc.}$$

Condensers connected in series

$$C_{(\text{Total})} = \frac{1}{\frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \text{ etc.}}$$

Formulae for Calculating Electrical Properties of Circuits

Desired Data	ALTERNATING CURRENT			Direct Current
	Single Phase	Two Phase* Four Wire	Three Phase	
KILOWATTS	$\frac{I E \cos \theta}{1000}$	$\frac{2 I E \cos \theta}{1000}$	$\frac{1.73 I E \cos \theta}{1000}$	$\frac{I E}{1000}$
KILOVOLT-AMPERES	$\frac{I E}{1000}$	$\frac{2 I E}{1000}$	$\frac{1.73 I E}{1000}$	$\frac{I E}{1000}$
HORSEPOWER OUTPUT,	$\frac{I E \cos \theta \times \text{Eff.}}{746}$	$\frac{2 I E \cos \theta \times \text{Eff.}}{746}$	$\frac{1.73 I E \cos \theta \times \text{Eff.}}{746}$	$\frac{I E \times \text{Eff.}}{746}$
AMPERES WHEN HORSEPOWER IS KNOWN	$\frac{\text{HP} \times 746}{E \cos \theta \times \text{Eff.}}$	$\frac{\text{HP} \times 746}{2 E \cos \theta \times \text{Eff.}}$	$\frac{\text{HP} \times 746}{1.73 E \cos \theta \times \text{Eff.}}$	$\frac{\text{HP} \times 746}{E \times \text{Eff.}}$
AMPERES WHEN KILOWATTS ARE KNOWN	$\frac{\text{KW} \times 1000}{E \cos \theta}$	$\frac{\text{KW} \times 1000}{2 E \cos \theta}$	$\frac{\text{KW} \times 1000}{1.73 E \cos \theta}$	$\frac{\text{KW} \times 1000}{E}$
AMPERES WHEN KILOVOLT-AMPERES ARE KNOWN	$\frac{\text{KVA} \times 1000}{E}$	$\frac{\text{KVA} \times 1000}{2 E}$	$\frac{\text{KVA} \times 1000}{1.73 E}$	$\frac{\text{KVA} \times 1000}{E}$
e_r WHEN $e_s, I, \cos \theta$ ARE KNOWN	$\sqrt{e_s^2 - I^2(X \cos \theta \mp R \sin \theta)^2} - I(R \cos \theta \pm X \sin \theta)$			.....

*In three wire two phase circuits, the current in the common conductor is 1.41 times that in either phase conductor.

NOTATION

$\cos \theta$ = Power factor of load
 E = Volts between conductors
 e = Volts to neutral
 Eff. = Efficiency of motor
 e_r = Volts at receiving end

e_s = Volts at sending end
 I = Line current amperes
 R = Resistance in ohms to neutral
 $\sin^2 \theta = 1 - \cos^2 \theta$
 X = Reactance in ohms to neutral

Where double signs, such as $\mp$ or $\pm$ are shown, use upper one for lagging and lower one for leading power factor.

WIRE TABLE, STANDARD ANNEALED COPPER
American Wire Gauge (B. & S.) English Units

Gauge No.	Diameter in mils at 20°C	Cross section at 20°C		Ohms per 1000 feet*			
		Circular mils	Sq. inches	0°C (32°F)	20°C (68°F)	50°C (122°F)	75°C (167°F)
0000	460.0	211600	0.1662	0.04516	0.04901	0.05479	0.05961
000	409.6	167800	.1313	.05695	.06180	.06909	.07516
00	364.8	133100	.1045	.07181	.07793	.08712	.09478
0	324.9	105500	.08289	.09055	.09827	.1099	.1195
1	289.3	83690	.06573	.1142	.1239	.1385	.1507
2	257.6	66370	.05213	.1440	.1563	.1747	.1900
3	229.4	52640	.04134	.1816	.1970	.2203	.2396
4	204.3	41740	.03278	.2289	.2485	.2778	.3022
5	181.9	33100	.02600	.2887	.3133	.3502	.3810
6	162.0	26250	.02062	.3640	.3951	.4416	.4805
7	144.3	20820	.01635	.4590	.4982	.5569	.6059
8	128.5	16510	.01297	.5788	.6282	.7023	.7640
9	114.4	13090	.01028	.7299	.7921	.8855	.9633
10	101.9	10380	.008155	.9203	.9989	1.117	1.215
11	90.74	8234	.006467	1.161	1.260	1.408	1.532
12	80.81	6530	.005129	1.463	1.588	1.775	1.931
13	71.96	5178	.004067	1.845	2.003	2.239	2.436
14	64.06	4107	.003225	2.327	2.525	2.823	3.071
15	57.07	3257	.002558	2.934	3.184	3.560	3.873
16	50.82	2583	.002028	3.700	4.016	4.489	4.884
17	45.26	2048	.001609	4.666	5.064	5.660	6.158
18	40.30	1624	.001276	5.883	6.385	7.138	7.765
19	35.89	1288	.001012	7.418	8.051	9.001	9.792
20	31.96	1022	.0008023	9.355	10.15	11.35	12.35
21	28.45	810.1	.0006363	11.80	12.80	14.31	15.57
22	25.35	642.4	.0005046	14.87	16.14	18.05	19.63
23	22.57	509.5	.0004002	18.76	20.36	22.76	24.76
24	20.10	404.0	.0003173	23.65	25.67	28.70	31.22
25	17.90	320.4	.0002517	29.82	32.37	36.18	39.36
26	15.94	254.1	.0001996	37.61	40.81	45.63	49.64
27	14.20	201.5	.0001583	47.42	51.47	57.53	62.59
28	12.64	159.8	.0001255	59.80	64.90	72.55	78.92
29	11.26	126.7	.00009953	75.40	81.83	91.48	99.52
30	10.03	100.5	.00007894	95.08	103.2	115.4	125.5
31	8.928	79.70	.00006260	119.9	130.1	145.5	158.2
32	7.950	63.21	.00004964	151.2	164.1	183.4	199.5
33	7.080	50.13	.00003937	190.6	206.9	231.3	251.6
34	6.305	39.75	.00003122	240.4	260.9	291.7	317.3
35	5.615	31.52	.00002476	303.1	329.0	367.8	400.1
36	5.000	25.00	.00001964	382.2	414.8	463.7	504.5
37	4.453	19.83	.00001557	482.0	523.1	584.8	636.2
38	3.965	15.72	.00001235	607.8	659.6	737.4	802.2
39	3.531	12.47	.000009793	766.4	831.8	929.8	1012
40	3.145	9.888	.000007766	966.5	1049	1173	1276

* Resistance at the stated temperatures of a wire whose length is 1000 feet at 20°C.

Wire Gauges

Combined Table of Sizes in the Principal Wire Gauges

SOLID WIRE					GAUGE NUMBERS		SOLID WIRE		SOLID WIRE		STRANDED WIRE	
Diameters		Cross Section			American Wire Gauge (A.S.J.)	Metric Wire Gauge	Diam. (Inches)	Cross Section (Square Inches)	Pounds per Foot	Kilograms per Kilometer	Pounds per Foot	Kilograms per Kilometer
Mils	Milli-meters	Square Mils	Circular Mils	Square Milli-meters								
1414.	35.93	1570800	2000000	1013.4	....	....	1.4142	1.5708	....	....	6175	9190
1325.	33.64	1374450	1750000	886.7	....	....	1.3229	1.3745	....	....	5403	8041
1225.	31.12	1178810	1500000	760.1	....	....	1.2247	1.1781	....	....	4631	6893
1118.	28.41	981750	1250000	633.4	....	....	1.1180	.9818	....	....	3859	5744
1000.	25.40	785450	1000000	506.7	....	....	1.0000	.7854	....	....	3087	4595
948.	24.09	706860	900000	456.0	....	....	.9487	.7069	....	....	2779	4136
894.	22.72	628320	800000	405.4	....	....	.8944	.6283	....	....	2470	3676
866.	22.00	589050	750000	380.0	....	....	.8660	.5891	....	....	2316	3446
836.7	21.24	549780	700000	354.7	....	....	.8367	.5498	....	....	2161	3217
774.6	19.67	471240	600000	304.0	....	....	.7746	.4712	....	....	1853	2757
707.1	17.96	392700	500000	253.4	....	....	.7071	.3927	....	....	1544	2298
632.5	16.07	314160	400000	202.7	....	....	.6325	.3142	....	....	1235	1838
591.6	15.03	274890	350000	177.3	....	....	.5916	.2749	....	....	1081	1608
547.7	13.91	235620	300000	152.0	....	....	.5477	.2356	....	....	926	1379
500.	12.70	196300	250000	126.7	....	....	.500	.1963	757	1128	772	1151
490.	12.45	188600	240100	121.7	....	....	.490	.1886	727	1082	742	1104
464.	11.79	169100	215300	109.1	....	....	.464	.1691	653	971	666	990
461.5	11.70	167300	213000	107.9	....	....	.4615	.1673	646	959	659	978
460.	11.68	166200	211600	107.2	4-0	....	.460	.1662	641	953	653	972
454.	11.53	161900	206100	104.4	....	....	.454	.1619	624	929	636	948
432.	10.97	146600	186600	94.56	....	....	.432	.1466	565	840	576	857
430.5	10.93	145600	185300	93.91	....	....	.4305	.1456	562	835	573	852
425.	10.80	141900	180600	91.52	....	....	.425	.1419	547	813	558	829
409.6	10.40	131800	167800	85.03	3-0	....	.4096	.1318	508	756	518	771
400.	10.16	125700	160000	81.07	....	....	.400	.1257	484	720	494	734
393.6	10.00	121800	155100	78.58	....	....	.3938	.1218	469	699	478	712
393.7	10.00	121700	155000	78.54	....	100	.3937	.1217	468	697	477	711
380.	9.652	113400	144400	73.17	....	....	.380	.1134	429	650	438	653
372.	9.449	108700	138400	70.12	....	....	.372	.1087	419	623	427	635
364.8	9.266	104500	133100	67.43	2-0	....	.3648	.1045	403	599	411	612
362.5	9.208	103200	131400	66.56	....	....	.3625	.1032	398	592	406	604
354.3	9.000	98610	125500	63.62	....	90	.3543	.09861	380	566	388	577
348.	8.839	95110	121100	61.36	....	....	.348	.09511	367	545	374	556
340.	8.636	90790	115600	58.58	....	....	.340	.09079	350	521	357	531
331.	8.407	86050	109600	55.52	....	....	.331	.08605	332	494	339	504
324.9	8.251	82890	105500	53.48	0	....	.3249	.08289	319	475	326	485
324.	8.230	82450	105000	53.19	....	....	.324	.08245	318	472	324	481
315.	8.000	77910	99200	50.27	....	60	.315	.07791	305	447	311	462
306.5	7.785	73780	93940	47.60	....	....	.3065	.07378	284	423	290	431
300.	7.620	70690	90000	45.60	....	....	.300	.07069	273	408	278	413
289.3	7.348	65730	83690	42.41	1	....	.2893	.06573	253	377	258	385
284.	7.214	63350	80660	40.87	....	....	.284	.06335	244	363	249	370
282.	7.188	62900	80090	40.58	....	....	.282	.06290	242	361	247	368
276.	7.010	59830	76180	38.60	....	....	.276	.05983	231	343	236	350
275.6	7.000	59650	75850	38.48	....	70	.2756	.05965	230	342	235	349
262.5	6.668	54120	68910	34.92	....	....	.2625	.05412	209	310	213	316
259.	6.579	52690	67080	33.99	....	....	.259	.05269	203	302	207	308
257.6	6.544	52130	66370	33.63	2	....	.2576	.05213	201	299	205	305
252.	6.401	49880	63500	32.18	....	....	.252	.04988	193	286	197	292
243.7	6.190	46640	59390	30.09	....	....	.2437	.04664	180	267	184	272
238.	6.045	44490	56640	28.70	....	....	.238	.04449	173	255	176	260
236.2	6.000	43830	55800	28.27	....	60	.2362	.04383	169	251	173	256
232.	5.893	42270	53820	27.27	....	....	.232	.04227	163	242	166	247
229.4	5.827	41340	52630	26.67	3	....	.2294	.04134	159	237	162	242
225.3	5.723	39870	50760	25.72	....	....	.2253	.03987	154	228	157	233
220.	5.588	38010	48400	24.52	....	....	.220	.03801	147	217	150	221
212.	5.385	35300	44940	22.77	....	....	.212	.03530	136	202	139	206
207.	5.258	33650	42850	21.71	....	....	.207	.03365	130	193	133	197
204.3	5.189	32780	41740	21.15	4	....	.2043	.03278	126	188	129	192
203.	5.156	32370	41210	20.88	....	....	.203	.03237	125	186	128	190
196.8	5.000	30430	38750	19.63	....	50	.1968	.03043	117	174	119	177
192.	4.877	28950	36860	18.68	....	....	.1920	.02895	112	166	114	169

Wire Gauges (Continued)

Combined Table of Sizes in the Principal Wire Gauges

SOLID WIRE		Cross Section			GAUGE NUMBERS		SOLID WIRE		SOLID WIRE		STRANDED WIRE	
Diameters					American Wire Gauge (B. & S.)	Metric Wire Gauge	Diam. (Inches)	Cross Section (Square Inches)	Pounds per M Foot	Kilo-grams per Kilo-meter	Pounds per M Foot	Kilo-grams per Kilo-meter
Mils	Milli-meters	Square Mils	Circular Mils	Square Milli-meters								
181.9	4.621	26000	33100	16.77	5	....	.1819	.02600	100	149	102	152
180.	4.572	25450	32400	16.42	....	....	.180	.02545	98.0	146	100	149
177.2	4.500	24650	31390	15.90	....	45	.1772	.02465	94.9	141	96.8	144
177.	4.496	24610	31330	15.87	....	....	.177	.02461	94.8	141	96.7	144
176.	4.470	24330	30980	15.70	....	....	.176	.02433	93.6	139	95.5	142
165.	4.191	21380	27220	13.80	....	....	.165	.02138	88.2	123	90.0	134
162.	4.115	20620	26250	13.30	6	....	.162	.02062	79.5	118	81.1	120
160.	4.064	20110	25600	12.97	....	....	.160	.02011	77.5	115	79.1	117
157.5	4.000	19480	24810	12.57	....	40	.1575	.01948	75.1	112	76.6	114
148.3	3.767	17270	21990	11.14	....	....	.1483	.01727	66.5	99.0	67.8	101.0
148.	3.759	17200	21900	11.10	....	....	.148	.01720	66.3	98.6	67.6	100.6
144.3	3.665	16350	20820	10.55	7	....	.1443	.01635	63.0	93.7	64.3	95.6
144.	3.658	16290	20740	10.51	....	....	.144	.01629	62.8	93.4	64.1	95.3
137.8	3.500	14910	18990	9.621	....	35	.1378	.01491	57.5	85.5	58.7	87.2
135.	3.429	14310	18220	9.235	....	....	.135	.01431	55.2	82.0	56.3	83.6
134.	3.404	14100	17960	9.098	....	....	.134	.01410	54.3	80.8	55.4	82.4
128.5	3.264	12970	16510	8.366	8	....	.1285	.01297	50.0	74.4	51.0	75.9
128.	3.251	12870	16380	8.302	....	....	.128	.01287	49.6	73.8	50.6	75.3
120.5	3.061	11400	14520	7.358	....	....	.1205	.01140	43.9	65.3	44.8	66.6
120.	3.048	11310	14400	7.297	....	....	.120	.01131	43.6	64.8	44.5	66.1
118.1	3.000	10960	13950	7.069	....	30	.1181	.01096	42.3	62.8	43.1	64.1
116.	2.946	10570	13460	6.818	....	....	.116	.01057	40.8	60.5	41.6	61.7
114.4	2.908	10280	13090	6.634	9	....	.1144	.01028	39.6	58.9	40.4	60.1
109	2.769	9331	11880	6.020	....	....	.109	.009331	35.9	53.5	36.6	54.6
105.5	2.680	8742	11130	5.640	....	....	.1055	.008742	33.7	50.2	34.4	51.2
104.	2.642	8495	10820	5.481	....	....	.104	.008495	32.7	48.7	33.4	49.7
101.9	2.588	8155	10380	5.261	10	....	.1019	.008155	31.4	46.8	32.0	47.7
98.42	2.500	7609	9687	4.909	....	25	.09842	.007609	29.3	43.6	29.9	44.5
95.	2.413	7088	9025	4.573	....	....	.095	.007088	27.3	40.6	27.8	41.4
92.	2.337	6648	8464	4.289	....	....	.092	.006648	25.6	38.1	26.1	38.9
91.5	2.324	6576	8372	4.242	....	....	.0915	.006576	25.3	37.7	25.8	38.5
90.74	2.305	6467	8234	4.172	11	....	.09074	.006467	24.9	37.1	25.4	37.8
83.	2.108	5411	6889	3.461	....	....	.083	.005411	20.8	31.0	21.2	31.6
80.81	2.053	5129	6530	3.309	12	....	.08081	.005129	19.8	29.4	20.2	30.0
80	2.032	5027	6400	3.243	....	....	.080	.005027	19.4	28.8	19.8	29.4
78.74	2.000	4869	6200	3.142	....	20	.07874	.004869	18.8	27.9	19.2	28.5
72.	1.829	4072	5184	2.627	....	....	.072	.004072	16.1	23.4	16.4	23.9
71.96	1.828	4067	5178	2.624	13	....	.07196	.004067	15.7	23.3	16.0	23.8
70.87	1.800	3944	5022	2.545	....	18	.07087	.003944	15.2	22.6	15.5	23.1
65.	1.651	3318	4225	2.141	....	....	.065	.003318	12.8	19.0	13.1	19.4
64.08	1.628	3225	4107	2.081	14	....	.06408	.003225	12.4	18.5	12.6	18.9
64	1.626	3217	4096	2.075	....	....	.064	.003217	12.3	18.4	12.5	18.8
62.99	1.600	3116	3968	2.011	....	16	.06299	.003116	12.0	17.8	12.2	18.2
62.5	1.588	3068	3906	1.979	....	....	.0625	.003068	11.8	17.6	12.0	18.0
58.	1.473	2642	3364	1.705	....	....	.058	.002642	10.2	15.1	10.4	15.4
57.07	1.450	2558	3257	1.650	15	....	.05707	.002558	9.86	14.7	10.1	15.0
56.	1.422	2463	3136	1.589	....	....	.056	.002463	9.52	14.1	9.71	14.4
55.12	1.400	2386	3038	1.539	....	14	.05512	.002386	9.21	13.7	9.39	14.0
54	1.372	2290	2916	1.478	....	....	.054	.002290	8.83	13.1	9.01	13.4
50.82	1.291	2028	2583	1.309	16	....	.05082	.002028	7.82	11.6	7.98	11.8
49.	1.245	1886	2401	1.217	....	....	.049	.001886	7.27	10.8	7.42	11.0
48	1.219	1810	2304	1.167	....	....	.048	.001810	6.98	10.4	7.02	10.6
47.5	1.207	1772	2256	1.143	....	....	.0475	.001772	6.84	10.2	6.98	10.4
47.24	1.200	1753	2232	1.131	....	12	.04724	.001753	6.76	10.0	6.90	10.2
45.26	1.150	1609	2048	1.038	17	....	.04526	.001609	6.20	9.23	6.32	9.41
42.	1.067	1385	1764	.8938	....	....	.042	.001385	5.34	7.94	5.45	8.10
41.	1.041	1320	1681	.8518	....	....	.041	.001320	5.09	7.57	5.19	7.72
40.3	1.024	1276	1624	.8231	18	....	.0403	.001276	4.92	7.32	5.02	7.47
40.	1.016	1257	1600	.8107	....	....	.040	.001257	4.84	7.21	4.94	7.35
39.37	1.000	1217	1550	.7854	....	10	.03937	.001217	4.70	6.98	4.79	7.12
36.	.9144	1018	1296	.6567	....	....	.036	.001018	3.93	5.84	4.01	5.96
35.89	.9116	1012	1288	.6527	19	....	.03589	.001012	3.90	5.80	3.98	5.92
35.43	.9000	986.1	1255	.6362	....	9	.03543	.0009861	3.82	5.77	3.90	5.81
35.	.8890	962.1	1225	.6207	....	....	.035	.0009621	3.71	5.52	3.78	5.63
34.8	.8839	951.1	1211	.6136	....	....	.0348	.0009511	3.67	5.46	3.74	5.57
32	.8128	804.2	1024	.5189	....	....	.032	.0008042	3.11	4.62	3.17	4.71
31.96	.8118	802.3	1022	.5176	20	....	.03196	.0008023	3.09	4.60	3.15	4.69
31.7	.8052	789.2	1005	.5092	....	....	.0317	.0007892	3.04	4.53	3.10	4.62
31.5	.8000	779.1	992	.5027	....	8	.0315	.0007791	3.01	4.47	3.07	4.55

Wire Gauges (Continued)

(Solid)

Diameters		Cross Section			Gauge Numbers		Diam. (Inches)	Cross Section (Square Inches)	Weight	
Mils	Milli- meters	Square Mils	Circular Mils	Square Milli- meters	American Wire Gauge (No. 25-42)	Metric Wire Gauge			Pounds per M Foot	Kilo- grams per Kilo- meter
28.6	.7264	642.4	818.0	.4145	...	...	.0286	.0006424	2.47	3.68
28.46	.7229	636.3	810.1	.4105	21	...	.02846	.0006363	2.45	3.65
28	.7112	615.9	784.0	.3973	...	...	.028	.0006158	2.37	3.53
27.56	.7000	596.5	759.5	.3848	...	7	.02756	.0005965	2.29	3.42
27.8	.6553	522.8	665.6	.3373	...	...	.0258	.0005228	2.13	3.00
25.35	.6438	504.6	642.4	.3255	22	...	.02535	.0005046	1.94	2.89
25.	.6350	490.9	625.0	.3167	...	...	.025	.0004909	1.89	2.82
24.	.6096	452.4	576.0	.2919	...	...	.024	.0004524	1.74	2.59
23.62	.6000	438.3	558.0	.2828	...	6	.02362	.0004383	1.69	2.52
23.	.5842	415.5	529.0	.2675	...	...	.023	.0004155	1.60	2.38
22.57	.5733	400.1	509.5	.2582	23	...	.02257	.0004001	1.54	2.30
22.	.5588	380.1	484.0	.2452	...	...	.022	.0003801	1.46	2.18
20.4	.5182	326.9	416.2	.2109	...	...	.0204	.0003269	1.26	1.88
20.1	.5106	317.3	404.0	.2047	24	...	.0201	.0003173	1.22	1.82
20	.5080	314.2	400.0	.2027	...	...	.020	.0003142	1.21	1.80
19.68	.5000	304.3	387.5	.1963	...	5	.01968	.0003043	1.17	1.75
18.1	.4597	257.3	327.6	.1660	...	...	.0181	.0002573	.992	1.48
18	.4572	254.5	324.0	.1642	...	...	.018	.0002545	.982	1.46
17.9	.4547	251.7	320.4	.1624	25	...	.0179	.0002517	.970	1.44
17.72	.4500	246.5	313.9	.1590	...	4.5	.01772	.0002465	.951	1.42
17.3	.4394	235.1	299.3	.1517	...	...	.0173	.0002351	.906	1.35
16.4	.4166	211.2	269.0	.1363	...	...	.0164	.0002112	.814	1.21
16.2	.4115	206.1	262.4	.1330	...	...	.0162	.0002061	.796	1.18
16	.4064	201.1	256.0	.1297	...	...	.016	.0002011	.775	1.15
15.94	.4049	199.6	254.1	.1288	26	...	.01594	.0001996	.769	1.14
15.75	.4000	194.8	248.0	.1257	...	4	.01575	.0001948	.751	1.12
15	.3810	176.7	225.0	.1140	...	...	.015	.0001767	.682	1.01
14.8	.3759	172.0	219.0	.1110	...	...	.0148	.0001720	.663	.987
14.2	.3606	158.3	201.5	.1021	27	...	.0142	.0001583	.610	.908
14	.3556	153.9	196.0	.09932	...	...	.014	.0001539	.593	.883
13.78	.3500	149.1	189.9	.09621	...	3.5	.01378	.0001491	.575	.855
13.6	.3454	145.3	185.0	.09372	...	...	.0136	.0001453	.560	.834
13.2	.3353	136.8	174.2	.08829	...	...	.0132	.0001368	.527	.785
13.	.3302	132.7	169.0	.08563	...	...	.013	.0001327	.511	.762
12.8	.3251	128.7	163.8	.08302	...	...	.0128	.0001287	.496	.738
12.64	.3211	125.2	159.8	.08098	28	...	.01264	.0001255	.484	.720
12.4	.3150	120.8	153.8	.07791	...	...	.0124	.0001208	.465	.693
12.	.3048	113.1	144.0	.07297	...	...	.012	.0001131	.437	.649
11.81	.3000	109.6	139.5	.07069	...	3	.01181	.0001096	.423	.628
11.8	.2997	109.4	139.2	.07055	...	...	.0118	.0001094	.422	.627
11.6	.2946	105.7	134.6	.06818	...	...	.0116	.0001057	.406	.606
11.26	.2859	99.54	126.7	.06422	29	...	.01126	.00009954	.384	.571
10.8	.2743	91.61	116.6	.05910	...	...	.0108	.00009161	.353	.525
10.4	.2642	84.95	108.2	.05481	...	...	.0104	.00008495	.327	.488
10.03	.2546	78.94	100.5	.05093	30	...	.01003	.00007894	.304	.453
10.	.2540	78.54	100.0	.05067	...	...	.010	.00007854	.302	.451
9.842	.2500	76.09	96.87	.04909	...	2.5	.009842	.00007609	.293	.436
9.5	.2413	70.88	90.25	.04573	...	...	.0095	.00007088	.273	.407
9.2	.2337	66.48	84.64	.04289	...	...	.0092	.00006648	.256	.382
9.	.2286	63.62	81.00	.04104	...	...	.009	.00006362	.245	.365
8.928	.2268	62.60	79.70	.04039	31	...	.008928	.00006260	.241	.359

Wire Gauges (Concluded)

(Solid)

Diameter		Cross Section			Gauge Numbers		Diam. (Inches)	Cross Section (Square Inches)	Weight	
Mils	Milli- meters	Square Mils	Circular Mils	Square Milli- meters	American Wire Gauge (B. & S.)	Metric Wire Gauge			Pounds per M Foot	Kilo- grams per Kilo- meter
8.5	.2159	56.75	72.25	.03661	....	....	.0085	.00005675	.219	.326
8.4	.2134	55.42	70.56	.03575	....	....	.0084	.00005542	.213	.318
8.	.2032	50.27	64.00	.03243	....	....	.008	.00005027	.194	.288
7.95	.2019	49.64	63.21	.03203	32	....	.00795	.00004964	.191	.285
7.874	.2000	48.69	62.00	.03142	....	2	.007874	.00004869	.188	.280
7.6	.1930	45.36	57.76	.02927	....	....	.0076	.00004536	.175	.260
7.5	.1905	44.18	56.25	.02850	....	1.6	.0075	.00004418	.170	.253
7.087	.1800	39.44	50.22	.02545	....	1.8	.007087	.00003944	.153	.227
7.08	.1798	39.37	50.13	.02540	33	....	.00708	.00003937	.152	.226
7.	.1778	38.48	49.00	.02483	....	....	.007	.00003848	.148	.221
6.8	.1727	36.32	46.24	.02343	....	....	.0068	.00003632	.139	.208
6.6	.1676	34.21	43.56	.02207	....	....	.0066	.00003421	.131	.196
6.305	.1601	31.22	39.75	.02014	34	....	.006305	.00003122	.120	.179
6.299	.1600	31.16	39.68	.02011	....	1.6	.006299	.00003116	.119	.178
6.2	.1575	30.19	38.44	.01948	....	....	.0062	.00003019	.116	.173
6.	.1524	28.27	36.00	.01824	....	....	.006	.00002827	.108	.162
5.906	.1500	27.39	34.87	.01767	....	1.5	.005906	.00002739	.105	.157
5.8	.1473	26.42	33.64	.01705	....	....	.0058	.00002642	.102	.151
5.615	.1426	24.76	31.52	.01597	35	....	.005615	.00002476	.0954	.142
5.512	.1400	23.86	30.38	.01539	....	1.4	.005512	.00002386	.0920	.136
5.5	.1397	23.76	30.25	.01533	....	....	.0055	.00002376	.0916	.136
5.2	.1321	21.24	27.04	.01370	....	....	.0052	.00002124	.0818	.121
5.	.1270	19.63	25.00	.01267	36	....	.005	.00001963	.0757	.113
4.8	.1219	18.10	23.04	.01167	....	....	.0048	.00001810	.0698	.104
4.724	.1200	17.53	22.32	.01131	....	1.2	.004724	.00001753	.0676	.101
4.6	.1168	16.62	21.16	.01072	....	....	.0046	.00001662	.0641	.0954
4.453	.1131	15.57	19.83	.01005	37	....	.004453	.00001557	.0600	.0893
4.4	.1118	15.21	19.36	.009810	....	....	.0044	.00001521	.0587	.0873
4.	.1016	12.57	16.00	.008107	....	....	.004	.00001257	.0484	.0721
3.965	.1007	12.35	15.72	.007967	38	....	.003965	.00001235	.0476	.0708
3.937	.1000	12.17	15.50	.007854	....	1	.003937	.00001217	.0468	.0698
3.6	.09144	10.18	12.96	.006567	....	....	.0036	.00001018	.0393	.0584
3.531	.08969	9.793	12.47	.006318	39	....	.003531	.000009793	.0377	.0562
3.2	.08128	8.042	10.24	.005189	....	....	.0032	.000008042	.0310	.0462
3.145	.07987	7.766	9.888	.005010	40	....	.003145	.000007766	.0299	.0445
2.8	.07113	5.159	7.842	.003973	41	....	.0028	.000006159	.0237	.0354
2.8	.07112	6.158	7.840	.003973	....	....	.0028	.000006158	.0237	.0354
2.494	.06334	4.884	6.219	.003151	42	....	.002494	.000004884	.0188	.0280
2.4	.06096	4.524	5.760	.002919	....	....	.0024	.000004524	.0174	.0260
2.221	.05641	3.873	4.932	.002499	43	....	.002221	.000003873	.0149	.0222
2.	.05080	3.142	4.000	.002027	....	....	.002	.000003142	.0121	.0180
1.978	.05023	3.072	3.911	.001982	44	....	.001978	.000003072	.0118	.0176
1.969	.05000	3.044	3.875	.001963	....	0.5	.001969	.000003044	.0117	.0175
1.761	.04473	2.436	3.102	.001572	45	....	.001761	.000002436	.0094	.0140
1.6	.04064	2.011	2.560	.001237	....	....	.0016	.000002011	.0077	.0115
1.568	.03964	1.932	2.460	.001246	46	....	.001568	.000001932	.0074	.0111
1.397	.03547	1.532	1.951	.0009884	47	....	.001397	.000001532	.0059	.0088
1.243	.03159	1.215	1.547	.0007838	48	....	.001243	.000001215	.0047	.0070
1.2	.03048	1.131	1.440	.0007297	....	....	.0012	.000001131	.0044	.0065
1.107	.02813	.9635	1.227	.0006216	49	....	.001107	.0000009635	.0037	.0055
1.	.02540	.7854	1.000	.0005067	....	....	.001	.0000007854	.0030	.0045
.9863	.02505	.7641	.9728	.0004929	50	....	.0009863	.0000007641	.0029	.0044

CONDUIT SIZES—RUBBER INSULATED, BRAID COVERED—600V.*

The Following Table Applies Only to Complete Conduit Systems, and Does Not Apply to Short Sections of Conduit Used for the Protection of Exposed Wiring From Mechanical Injury.

No.	Size of Conductor	NUMBER OF WIRES IN ONE CONDUIT									Size of Conductor	MINIMUM SIZE OF CONDUIT IN INCHES									NUMBER OF WIRES IN ONE CONDUIT								
		MINIMUM SIZE OF CONDUIT IN INCHES										MINIMUM SIZE OF CONDUIT IN INCHES									MINIMUM SIZE OF CONDUIT IN INCHES								
		1	2	3	4	5	6	7	8	9		1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
14	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	550,000	$1\frac{1}{2}$	3	$3\frac{1}{2}$	4	$4\frac{1}{2}$	5	...	...	...	...	...	...	...	...	...	...	...	
12	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$1\frac{1}{4}$	600,000	2	3	$3\frac{1}{2}$	4	$4\frac{1}{2}$	5	...	...	...	...	...	...	...	...	...	...	...	
10	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$1\frac{1}{4}$	650,000	2	3	$3\frac{1}{2}$	4	...	...	...	...	...	...	...	...	...	...	...	...	...	
8	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$1\frac{1}{4}$	700,000	2	3	$3\frac{1}{2}$	$4\frac{1}{2}$	...	...	...	...	...	...	...	...	...	...	...	...	...	
6	$\frac{3}{4}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	2	750,000	2	3	$3\frac{1}{2}$	$4\frac{1}{2}$	...	...	...	...	...	...	...	...	...	...	...	...	...	
5	$\frac{3}{4}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	2	800,000	2	3	$3\frac{1}{2}$	$4\frac{1}{2}$	...	...	...	...	...	...	...	...	...	...	...	...	...	
4	$\frac{3}{4}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	2	850,000	2	3	$3\frac{1}{2}$	4	$4\frac{1}{2}$	...	...	...	...	...	...	...	...	...	...	...	...	
3	$\frac{3}{4}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	2	900,000	2	3	$3\frac{1}{2}$	4	$4\frac{1}{2}$	...	...	...	...	...	...	...	...	...	...	...	...	
2	$\frac{3}{4}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	2	950,000	2	4	4	5	...	...	...	...	...	...	...	...	...	...	...	...	...	
1	$\frac{3}{4}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	3	1,000,000	2	4	4	5	...	...	...	...	...	...	...	...	...	...	...	...	...	
0	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	3	1,100,000	2	4	4	$4\frac{1}{2}$	...	...	...	...	...	...	...	...	...	...	...	...	...	
00	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	3	1,200,000	2	4	$4\frac{1}{2}$	$4\frac{1}{2}$	...	...	...	...	...	...	...	...	...	...	...	...	...	
000	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$3\frac{1}{2}$	1,250,000	2	4	$4\frac{1}{2}$	$4\frac{1}{2}$	...	...	...	...	...	...	...	...	...	...	...	...	...	
0000	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$3\frac{1}{2}$	1,300,000	2	4	$4\frac{1}{2}$	$4\frac{1}{2}$	...	...	...	...	...	...	...	...	...	...	...	...	...	
200,000 C.M.	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	4	1,400,000	2	4	$4\frac{1}{2}$	$4\frac{1}{2}$	...	...	...	...	...	...	...	...	...	...	...	...	...	
225,000	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	...	1,500,000	2	4	$4\frac{1}{2}$	$4\frac{1}{2}$	...	...	...	...	...	...	...	...	...	...	...	...	...	
250,000	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	...	1,600,000	2	4	$4\frac{1}{2}$	$4\frac{1}{2}$	...	...	...	...	...	...	...	...	...	...	...	...	...	
300,000	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	...	1,700,000	2	4	$4\frac{1}{2}$	$4\frac{1}{2}$	...	...	...	...	...	...	...	...	...	...	...	...	...	
350,000	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	...	1,750,000	3	5	5	6	...	...	...	...	...	...	...	...	...	...	...	...	...	
400,000	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	...	1,800,000	3	5	5	6	...	...	...	...	...	...	...	...	...	...	...	...	...	
450,000	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	...	1,900,000	3	5	5	6	...	...	...	...	...	...	...	...	...	...	...	...	...	
500,000	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	...	2,000,000	3	5	5	6	...	...	...	...	...	...	...	...	...	...	...	...	...	

* 1937 N.E. Code

CONDUIT SIZES—LEAD COVERED—600 V.*

The Following Table Applies Only to Complete Conduit Systems. and Does Not Apply to Short Sections of Conduit Used for the Protections of Exposed Wiring From Mechanical Injury.

Size of Conductor AWG or C.M.	Number of Conductors in One Conduit or Tubing											
	Single Conductor Cable				2-Conductor Cable				3-Conductor Cable			
	1	2	3	4	1	2	3	4	1	2	3	4
14	$\frac{1}{8}$	$\frac{3}{8}$	$\frac{3}{8}$	1	$\frac{1}{8}$	1	1	$1\frac{1}{4}$	$\frac{3}{4}$	$1\frac{1}{4}$	$1\frac{1}{2}$	$1\frac{1}{2}$
12	$\frac{1}{4}$	$\frac{3}{4}$	$\frac{3}{4}$	1	$\frac{1}{4}$	$1\frac{1}{4}$	$1\frac{1}{4}$	$1\frac{1}{2}$	1	$1\frac{1}{2}$	$1\frac{1}{2}$	2
10	$\frac{1}{2}$	$\frac{3}{4}$	1	1	$\frac{1}{2}$	$1\frac{1}{4}$	$1\frac{1}{4}$	$1\frac{1}{2}$	1	$1\frac{1}{2}$	2	2
8	$\frac{1}{2}$	1	$1\frac{1}{4}$	$1\frac{1}{2}$	1	$1\frac{1}{4}$	$1\frac{1}{2}$	2	1	2	2	$2\frac{1}{2}$
6	$\frac{3}{4}$	$1\frac{1}{4}$	$1\frac{1}{2}$	$1\frac{1}{2}$	$1\frac{1}{4}$	$1\frac{1}{2}$	2	$2\frac{1}{2}$	$1\frac{1}{4}$	$2\frac{1}{2}$	3	3
4	$\frac{3}{4}$	$1\frac{1}{4}$	$1\frac{1}{2}$	$1\frac{1}{2}$	$1\frac{1}{4}$	2	$2\frac{1}{2}$	$2\frac{1}{2}$	$1\frac{1}{2}$	3	3	$3\frac{1}{2}$
3	$\frac{3}{4}$	$1\frac{1}{4}$	$1\frac{1}{2}$	2	$1\frac{1}{4}$	2	$2\frac{1}{2}$	3	$1\frac{1}{2}$	3	3	$3\frac{1}{2}$
2	1	$1\frac{1}{4}$	$1\frac{1}{2}$	2	$1\frac{1}{4}$	2	$2\frac{1}{2}$	3	$1\frac{1}{2}$	3	$3\frac{1}{2}$	4
1	1	$1\frac{1}{2}$	2	2	$1\frac{1}{2}$	$2\frac{1}{2}$	3	$3\frac{1}{2}$	2	$3\frac{1}{2}$	4	$4\frac{1}{2}$
0	1	2	2	$2\frac{1}{2}$	2	$2\frac{1}{2}$	3	$3\frac{1}{2}$	2	4	$4\frac{1}{2}$	5
00	1	2	2	$2\frac{1}{2}$	2	3	$3\frac{1}{2}$	4	$2\frac{1}{2}$	4	$4\frac{1}{2}$	5
000	$1\frac{1}{4}$	2	$2\frac{1}{2}$	$2\frac{1}{2}$	2	3	$3\frac{1}{2}$	4	$2\frac{1}{2}$	$4\frac{1}{2}$	$4\frac{1}{2}$	6
0000	$1\frac{1}{4}$	$2\frac{1}{2}$	$2\frac{1}{2}$	3	$2\frac{1}{2}$	3	$3\frac{1}{2}$	$4\frac{1}{2}$	3	5	6	6
250,000	$1\frac{1}{4}$	$2\frac{1}{2}$	3	3	...	...	...	...	3	6	6	...
300,000	$1\frac{1}{2}$	3	3	$3\frac{1}{2}$	...	...	...	...	$3\frac{1}{2}$	6	6	...
350,000	$1\frac{1}{2}$	3	3	$3\frac{1}{2}$	...	...	...	...	$3\frac{1}{2}$	6	6	...
400,000	$1\frac{1}{2}$	3	3	$3\frac{1}{2}$	...	...	...	...	$3\frac{1}{2}$	6	6	...
450,000	$1\frac{1}{2}$	3	3	4	...	...	...	...	4	6	6	...
500,000	$1\frac{1}{2}$	3	$3\frac{1}{2}$	4	...	...	...	...	4	6	...	...
600,000	2	$3\frac{1}{2}$	4	$4\frac{1}{2}$	...	...	...	...	...	...	...	...
700,000	2	4	4	5	...	...	...	...	...	...	...	...
750,000	2	4	4	5	...	...	...	...	...	...	...	...
800,000	2	4	$4\frac{1}{2}$	5	...	...	...	...	...	...	...	...
900,000	$2\frac{1}{2}$	4	$4\frac{1}{2}$	5	...	...	...	...	...	...	...	...
1,000,000	$2\frac{1}{2}$	$4\frac{1}{2}$	$4\frac{1}{2}$	6	...	...	...	...	...	...	...	...
1,250,000	3	5	5	6	...	...	...	...	...	...	...	...
1,500,000	3	5	6	6	...	...	...	...	...	...	...	...
1,750,000	3	6	6	...	...	...	...	...	...	...	...	...
2,000,000	$3\frac{1}{2}$	6	6	...	...	...	...	...	...	...	...	...

The above sizes apply to straight runs or with nominal offsets equivalent to not more than two quarter-bends.

It is recommended that bends have a minimum radius of curvature at the inner edge of the bend of not less than 10 times the internal diameter of the conduit or tubing.

* 1937 N.E. Code

WIRE SIZES FOR MOTOR CIRCUITS

1937 N. E. Code—Amperes at Full Load

SINGLE-PHASE A-C. MOTORS

H.P.	110V.	220V.*	440V.	H.P.	110V.	220V.*	440V.
$\frac{1}{8}$	3.34	1.67	...	2	20	10	....
$\frac{1}{4}$	4.8	2.4	...	3	28	14	....
$\frac{1}{2}$	7	3.5	...	5	46	23	17.
$\frac{3}{4}$	9.4	4.7	...	$7\frac{1}{2}$	68	34	21.5
1	11	5.5	...	10	86	43	....
$1\frac{1}{2}$	15.2	7.6	...	....	..	..	....

WIRE SIZES FOR MOTOR CIRCUITS—Continued

1937 N. E. CODE—Amperes at Full Load

TWO-PHASE A-C. MOTORS (4-Wire)

H.P.	INDUCTION TYPE SQUIRREL-CAGE AND WOUND ROTOR					SYNCHRONOUS TYPE UNITY POWER FACTOR			
	110V.	220V.	440V.	550V.	2200 V.	220V.	440V.	550V.	2200 V.
$\frac{1}{2}$	4.3	2.2	1.1	.9	..	...	...	...	....
$\frac{3}{4}$	4.7	2.4	1.2	1.0	..	...	...	...	....
1	5.7	2.9	1.4	1.2	..	...	...	...	....
$1\frac{1}{2}$	7.7	4.0	2	1.6	..	...	...	...	....
2	10.4	5	3	2.0	..	...	...	...	....
3	...	8	4	3.0	..	...	...	...	....
5	...	13	7	6	..	...	...	...	....
$7\frac{1}{2}$	...	19	9	7	..	...	...	...	....
10	...	24	12	10	..	...	...	...	....
15	...	33	16	13	..	...	...	...	....
20	...	45	23	19	..	...	...	...	....
25	...	55	28	22	6	47	24	19	4.7
30	...	67	34	27	7	56	29	23	5.7
40	...	88	44	35	9	75	37	31	7.5
50	...	108	54	43	11	94	47	38	9.4
60	...	129	65	52	13	111	56	44	11.3
75	...	156	78	62	16	140	70	57	14
100	...	212	106	85	22	182	93	74	18
125	...	268	134	108	27	228	114	93	23
150	...	311	155	124	31	...	137	110	28
200	...	415	208	166	43	...	182	145	37

THREE-PHASE A-C. MOTORS

H.P.	INDUCTION TYPE SQUIRREL-CAGE AND WOUND ROTOR					SYNCHRONOUS TYPE UNITY POWER FACTOR			
	110V.	220 V.*	440V.	550V.	2200 V.	220 V.*	440V.	550V.	2200 V.
$\frac{1}{2}$	5	2.5	1.3	1	..	...	...	...	....
$\frac{3}{4}$	5.4	2.8	1.4	1.1	..	...	...	...	....
1	6.6	3.3	1.7	1.3	..	...	...	...	....
$1\frac{1}{2}$	9.4	4.7	2.4	2.0	..	...	...	...	....
2	12	6	3	2.4	..	...	...	...	....
3	...	9	4.5	4	..	...	...	...	....
5	...	15	7.5	6	..	...	...	...	....
$7\frac{1}{2}$	...	22	11	9	..	...	...	...	....
10	...	27	14	11	..	...	...	...	....
15	...	38	19	15	..	...	...	...	....
20	...	52	26	21	..	...	...	...	....
25	...	64	32	26	7	54	27	22	5.4
30	...	77	39	31	8	65	33	26	6.5
40	...	101	51	40	10	86	43	35	8.6
50	...	125	63	50	13	108	54	44	10.8
60	...	149	75	60	15	128	64	51	13
75	...	180	90	72	19	161	81	65	16
100	...	246	123	98	25	211	106	85	21
125	...	310	155	124	32	264	132	106	26
150	...	360	180	144	36	...	158	127	32
200	...	480	240	195	49	...	210	168	42

* For full-load currents of 208 and 200-volt motors, increase the corresponding 220-volt motor full-load current by 6 and 10 per cent, respectively.
(Continued on next page)

WIRE SIZES FOR MOTOR CIRCUITS—Continued

D-C. MOTORS

Amperes at Full Load

H.P.	115V.	230V.	550V.	H.P.	115V.	230V.	550V.
$\frac{1}{2}$	4.5	2.3	...	25	185	92	38
$\frac{3}{4}$	6.5	3.3	1.4	30	220	110	45
1	8.4	4.2	1.7	40	294	146	61
$1\frac{1}{2}$	12.5	6.3	2.6	50	364	180	75
2	16.1	8.3	3.4	60	436	215	90
3	23.0	12.3	5.0	75	540	268	111
5	40	19.8	6.2	100	...	357	146
$7\frac{1}{2}$	58	28.7	12.0	125	...	443	184
10	75	38	16	150	...	...	202
15	112	56	23	200	...	...	295
20	140	74	30				

CORRESPONDING CONDUCTOR SIZE

For Amperes at Full Load

Motor Rating Amperes	Rubber Insulation	Motor Rating Amperes	Rubber Insulation
1 - 12	No. 14	170 - 180	4/0
13 & 14	No. 12	185 & 190	250 M.C.M.
15 & 16	No. 12	195 & 200	250
17 - 20	No. 10	210	300
22 & 24	No. 8	220	300
26 & 28	No. 8	230 & 240	350
30 & 32	No. 6	250 & 260	400
34 - 40	No. 6	270 & 280	500
42 & 44	No. 5	290	500
46 & 48	No. 4	300	500
50 & 52	No. 4	320	500
54 & 56	No. 4	340 & 360	600
58 - 64	No. 3	380	700
66 & 68	No. 2	400	700
70 & 72	No. 2	420	800
74 & 76	No. 1	440	800
78 & 80	No. 1	460 & 480	900
82 - 88	No. 1/0	500 & 520	1000
90 - 96	No. 1/0	540	1100
98 & 100	No. 1/0	560	1200
105 - 120	No. 2/0	580	1200
125 - 140	No. 3/0	600	1300
145 - 160	No. 200	625	1400
165	No. 4/0	...	....

CONDUIT SIZES

CABLES ABOVE 600 VOLTS, ALSO CONTROL CABLES

Cables of Equal Diameter

Number of Cables in Conduit	NOMINAL SIZE OF CONDUIT*											
	½"	¾"	1"	1¼"	1½"	2"	2½"	3"	3½"	4"	4½"	5"
1	.46	.61	.78	1.03	1.20	1.54	1.84	2.29	2.67	3.01	3.37	3.77
2	.25	.33	.42	.55	.64	.82	.98	1.22	1.42	1.61	1.80	2.02
3	.23	.31	.39	.52	.60	.77	.92	1.15	1.33	1.50	1.68	1.89
4	.20	.26	.33	.44	.51	.65	.78	.97	1.13	1.27	1.42	1.59
5		.22	.28	.37	.43	.55	.66	.82	.95	1.08	1.21	1.35
6		.20	.26	.34	.40	.51	.61	.76	.89	1.00	1.12	1.25
7		.19	.24	.32	.37	.47	.57	.70	.82	.93	1.04	1.16
8			.22	.30	.35	.44	.53	.66	.76	.86	.97	1.08
9			.21	.28	.33	.42	.50	.62	.72	.81	.91	1.02

MAXIMUM CABLE DIAMETER IN INCHES

EXAMPLE: A 1½" conduit will accommodate 3 cables with diam. .52" to .60".

* Conduit sizes are based on a straight run of 200', 100' with 2-90° bends or 50' with 3-90° bends. For installations exceeding these limiting conditions use one or two conduit sizes larger.

DIMENSIONS OF CONDUIT OR TUBING

1937 N. E. Code

Size (Inches)	Internal Diameter (Inches)	Area (Sq. Inches)	Size (Inches)	Internal Diameter (Inches)	Area (Sq. Inches)
½	.622	.30	3	3.068	7.38
¾	.824	.53	3½	3.548	9.90
1	1.049	.86	4	4.026	12.72
1¼	1.380	1.50	4½	4.506	15.95
1½	1.610	2.04	5	5.047	20.00
2	2.067	3.36	6	6.065	28.89
2½	2.469	4.79			

The following pages show temperatures on Fahrenheit and Centigrade thermometers.

Equivalent Temperature Readings for Fahrenheit and Centigrade Scales

Fahren- heit Degs.	Centi- grade Degs.	Fahren- heit Degs.	Centi- grade Degs.	Fahren- heit Degs.	Centi- grade Degs.	Fahren- heit Degs.	Centi- grade Degs.
-459.4	-273	-21.	-29.4	17.6	-8.	56.	13.3
-436.	-270.	-20.2	-29.	18.	-7.8	57.	13.9
-418.	-260.	-20.	-28.9	19.	-7.2	57.2	14.
-400.	-240.	-19.	-28.3	19.4	-7.	58.	14.4
-382.	-230.	-18.4	-28.	20.	-6.7	59.	15.
-364.	-220.	-18.	-27.8	21.	-6.1	60.	15.6
-346.	-210.	-17.	-27.2	21.2	-6.	60.8	16.
-328.	-200.	-16.6	-27.	22.	-5.6	61.	16.1
-310.	-190.	-16.	-26.7	23.	-5.	62.	16.7
-292.	-180.	-15.	-26.1	24.	-4.4	62.6	17.
-274.	-170.	-14.8	-26.	24.8	-4.	63.	17.2
-256.	-160.	-14.	-25.6	25.	-3.9	64.	17.8
-238.	-150.	-13.	-25.	26.	-3.3	64.4	18.
-220.	-140.	-12.	-24.4	26.6	-3.	65.	18.3
-202.	-130.	-11.2	-24.	27.	-2.8	66.	18.9
-184.	-120.	-11.	-23.9	28.	-2.2	66.2	19.
-166.	-110.	-10.	-23.3	28.4	-2.	67.	19.4
-148.	-100.	-9.4	-23.	29.	-1.7	68.	20.
-139.	-95.	-9.	-22.8	30.	-1.1	69.	20.6
-130.	-90.	-8.	-22.2	30.2	-1.	69.8	21.
-121.	-85.	-7.6	-22.	31.	-0.6	70.	21.1
-112.	-80.	-7.	-21.7	32.	0.	71.	21.7
-103.	-75.	-6.	-21.1	33.	+0.6	71.6	22.
-94.	-70.	-5.8	-21.	33.8	1.	72.	22.2
-85.	-65.	-5.	-20.6	34.	1.1	73.	22.8
-78.	-60.	-4.	-20.	35.	1.7	73.4	23.
-67.	-55.	-3.	-19.4	35.6	2.	74.	23.3
-58.	-50.	-2.2	-19.	36.	2.2	75.	23.9
-49.	-45.	-2.	-18.9	37.	2.8	75.2	24.
-40.	-40.	-1.	-18.3	37.4	3.	76.	24.4
-39.	-39.4	-0.4	-18.	38.	3.3	77.	25.
-38.2	-39.	0.	-17.8	39.	3.9	78.	25.6
-38.	-38.9	+1.	-17.2	39.2	4.	78.8	26.
-37.	-38.3	1.4	-17.	40.	4.4	79.	26.1
-36.4	-38.	2.	-16.7	41.	5.	80.	26.7
-36.	-37.8	3.	-16.1	42.	5.6	80.6	27.
-35.	-37.2	3.2	-16.	42.8	6.	81.	27.2
-34.6	-37.	4.	-15.6	43.	6.1	82.	27.8
-34.	-36.7	5.	-15.	44.	6.7	82.4	28.
-33.	-36.1	6.	-14.4	44.6	7.	83.	28.3
-32.8	-36.	6.8	-14.	45.	7.2	84.	28.9
-32.	-35.6	7.	-13.9	46.	7.8	84.2	29.
-31.	-35.	8.	-13.3	46.4	8.	85.	29.4
-30.	-34.4	8.6	-13.	47.	8.3	86.	30.
-29.2	-34.	9.	-12.8	48.	8.9	87.	30.6
-29.	-33.9	10.	-12.2	48.2	9.	87.8	31.
-28.	-33.3	10.4	-12.	49.	9.4	88.	31.1
-27.4	-33.	11.	-11.7	50.	10.	89.	31.7
-27.	-32.8	12.	-11.1	51.	10.6	89.6	32.
-26.	-32.2	12.2	-11.	51.8	11.	90.	32.2
-25.6	-32.	13.	-10.6	52.	11.1	91.	32.8
-25.	-31.7	14.	-10.	53.	11.7	91.4	33.
-24.	-31.1	15.	-9.4	53.6	12.	92.	33.3
-23.8	-31.	15.8	-9.	54.	12.2	93.	33.9
-23.	-30.6	16.	-8.9	55.	12.8	93.2	34.
-22.	-30.	17.	-8.3	55.4	13.	94.	34.4

Equivalent Temperature Readings for Fahrenheit and Centigrade Scales

Fahren- heit Degr.	Centi- grade Degr.	Fahren- heit Degr.	Centi- grade Degr.	Fahren- heit Degr.	Centi- grade Degr.	Fahren- heit Degr.	Centi- grade Degr.
95.	35.	134.	56.7	172.4	78.	211.	99.4
96.	35.6	134.6	57.	173.	78.3	212.	100.
96.8	36.	135.	57.2	174.	78.9	213.	100.6
97.	36.1	136.	57.8	174.2	79.	213.8	101.
98.	36.7	136.4	58.	175.	79.4	214.	101.1
98.6	37.	137.	58.3	176.	80.	215.	101.7
99.	37.2	138.	58.9	177.	80.6	215.6	102.
100.	37.8	138.2	59.	177.8	81.	216.	102.2
100.4	38.	139.	59.4	178.	81.1	217.	102.8
101.	38.3	140.	60.	179.	81.7	217.4	103.
102.	38.9	141.	60.6	179.6	82.	218.	103.3
102.2	39.	141.8	61.	180.	82.2	219.	103.9
103.	39.4	142.	61.1	181.	82.8	219.2	104.
104.	40.	143.	61.7	181.4	83.	220.	104.4
105.	40.6	143.6	62.	182.	83.3	221.	105.
105.8	41.	144.	62.2	183.	83.9	222.	105.6
106.	41.1	145.	62.8	183.2	84.	222.8	106.
107.	41.7	145.4	63.	184.	84.4	223.	106.1
107.6	42.	146.	63.3	185.	85.	224.	106.7
108.	42.2	147.	63.9	186.	85.6	224.6	107.
109.	42.8	147.2	64.	186.8	86.	225.	107.2
109.4	43.	148.	64.4	187.	86.1	226.	107.8
110.	43.3	149.	65.	188.	86.7	226.4	108.
111.	43.9	150.	65.6	188.6	87.	227.	108.3
111.2	44.	150.8	66.	189.	87.2	228.	108.9
112.	44.4	151.	66.1	190.	87.8	228.2	109.
113.	45.	152.	66.7	190.4	88.	229.	109.4
114.	45.6	152.6	67.	191.	88.3	230.	110.
114.8	46.	153.	67.2	192.	88.9	231.	110.6
115.	46.1	154.	67.8	192.2	89.	231.8	111.
116.	46.7	154.4	68.	193.	89.4	232.	111.1
116.6	47.	155.	68.3	194.	90.	233.	111.7
117.	47.2	156.	68.9	195.	90.6	233.6	112.
118.	47.8	156.2	69.	195.8	91.	234.	112.3
118.4	48.	157.	69.4	196.	91.1	235.	112.8
119.	48.3	158.	70.	197.	91.7	235.4	113.
120.	48.9	159.	70.6	197.6	92.	236.	113.3
120.2	49.	159.8	71.	198.	92.2	237.	113.9
121.	49.4	160.	71.1	199.	92.8	237.2	114.
122.	50.	161.	71.7	199.4	93.	238.	114.4
123.	50.6	161.6	72.	200.	93.3	239.	115.
123.8	51.	162.	72.2	201.	93.9	240.	115.6
124.	51.1	163.	72.8	201.2	94.	240.8	116.
125.	51.7	163.4	73.	202.	94.4	241.	116.1
125.6	52.	164.	73.3	203.	95.	242.	116.7
126.	52.2	165.	73.9	204.	95.6	242.6	117.
127.	52.8	165.2	74.	204.8	96.	243.	117.2
127.4	53.	166.	74.4	205.	96.1	244.	117.8
128.	53.3	167.	75.	206.	96.7	244.4	118.
129.	53.9	168.	75.6	206.6	97.	245.	118.3
129.2	54.	168.8	76.	207.	97.2	246.	118.9
130.	54.4	169.	76.1	208.	97.8	246.2	119.
131.	55.	170.	76.7	208.4	98.	247.	119.4
132.	55.6	170.6	77.	209.	98.3	248.	120.
132.8	56.	171.	77.2	210.	98.9	249.	120.6
133.	56.1	172.	77.8	210.2	99.	249.8	121.

Conversion Tables

MULTIPLY	BY	TO OBTAIN
Inches	1,000.	Mils
Mils	.001	Inches
Inches	25.4	Millimeters
Millimeters	.03937	Inches
Mils	.0254	Millimeters
Millimeters	39.3701	Mils
Inches	2.54	Centimeters
Centimeters	.3937	Inches
Inches	.0254	Meters
Meters	39.3701	Inches
Feet	30.48	Centimeters
Centimeters	.03281	Feet
Feet	.3048	Meters
Meters	3.2808	Feet
Square Inches	1,000,000.	Square Mils
Square Mils	.000001	Square Inches
Square Inches	1,273,240.	Circular Mils
Circular Mils	.0000007854	Square Inches
Square Mils	1.2732	Circular Mils
Circular Mils	.7854	Square Mils
Circular Mils	.0005066	Square Millimeters
Square Millimeters	1,973.51	Circular Mils
Square Inches	645.16	Square Millimeters
Square Millimeters	.00155	Square Inches
Square Inches	6.4516	Square Centimeters
Square Centimeters	.155	Square Inches
Square Feet	.0929	Square Meters
Square Meters	10.764	Square Feet
Resistance at 20° C.	.9827	Resistance at 60° F.
Resistance at 60° F.	1.0176	Resistance at 20° C.
Ohms per Kilometer	.3048	Ohms per 1000 Feet
Ohms per 1000 Feet	3.2808	Ohms per Kilometer
Pounds per 1000 Feet	1.488	Kilograms per Kilometer
Kilograms per Kilometer	.6719	Pounds per 1000 Feet
Kilograms	2.2046	Pounds



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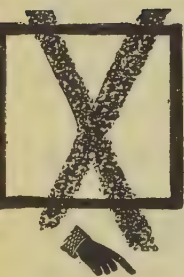
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